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DEVELOPMENT OF LUBRICANT SCREENING TESTS AND EVALUATION OF LUBRICANTS FOR GAS TURBINE ENGINES FOR COMMERCIAL SUPERSONIC TRANSPORT

PROGRESS REPORT NO. 1
Contract AF 33(657)-9248
Project 648D

B. B. Baber, J. P. Cuellar, P. M. Ku
C. W. Lawler, H. E. Staph

to

Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

August 1, 1962

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Department of Aerospace Propulsion Research

(6)

DEVELOPMENT OF LUBRICANT SCREENING TESTS AND EVALUATION OF LUBRICANTS FOR GAS TURBINE ENGINES FOR COMMERCIAL SUPERSONIC TRANSPORT.

(7) PROGRESS REP~~OR~~T NO. 1, 1 May - 31 Jul 62,
(15) Contract AF 33(657)-9248,
(16) Proj~~ect~~ 648D

(10) by
B. B. Baber, J. P. Cuellar, P M Ku,
C W. Lawler, H E Staph,

to

Aeronautical Systems Division
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

August 1, 1962

APPROVED

for P. M Ku, Director
Department of Aerospace
Propulsion Research

FOREWORD

The work described in this report was performed at Southwest Research Institute, San Antonio, Texas, under USAF Contract 33(657)-9248, Project 648D, and administered by the Nonmetallic Materials Laboratory, Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. G. A. Beane of the Nonmetallic Materials Laboratory was the project engineer.

This report covers the work performed in the period of May 1, 1962 through July 31, 1962.

ABSTRACT

This progress report describes the work performed in the initial period of May 1, 1962 through July 31, 1962 on a program to develop lubricant screening tests and to evaluate lubricants for gas turbine engines for the commercial supersonic transport. During the ~~subject~~ period, the effort was directed mainly toward three areas. gear load-carrying capacity bearing fatigue, and lubricant oxidation-corrosion

In the gear load-carrying capacity phase, considerable dynamic calibration of the test equipment and exploratory testing of lubricants ~~have been~~ made at temperatures up to 500°F The bearing fatigue phase ~~has been~~ confined to design studies on a 3-ball/cone fatigue tester with a temperature capability of 800°F. The lubricant oxidation-corrosion phase ~~has~~ encompassed further work on a 425°F oxidation-corrosion test procedure previously developed, design and construction of an oxidation-corrosion test apparatus with a temperature capability of 800°F, and exploratory testing of lubricants at 500°F.

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I. INTRODUCTION

The present program, initiated on May 1, 1962 under USAF Contract AF 33(657)-9248, Project 648D, is concerned with the development of lubricant screening tests and the evaluation of lubricants for gas turbine engines for the commercial supersonic transport. This program is part of a broad program of research and study to investigate the technical and economic problems related to the commercial supersonic transport being conducted with the financial support of the Federal Aviation Agency, Washington, D. C. Technical administration of this program is the responsibility of the Nonmetallic Materials Laboratory, Directorate of Materials and Processes, Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

The commercial supersonic transport under research study is anticipated to cruise at a speed in the range of Mach 3. At this speed, the lubricant in the sump of the lubrication system is expected to reach a temperature in the neighborhood of 500°F. For this reason, the thermal, oxidative. deposit-forming, and material-compatibility characteristics of lubricants at temperatures at the 500°F level are of vital interest. In addition, due to considerations of weight and reliability, the capability of lubricants to sustain reasonably high gear and bearing loads over extended periods of operation is also important. At the present time, no established test methods are available to evaluate the suitability of lubricants for these severe operating conditions. The objective of the present program is to develop such test methods and to obtain basic data on the performance characteristics of candidate lubricants using the test methods developed.

Since April 1, 1953, Southwest Research Institute has been engaged in lubrication research and lubricant test method development for aviation gas turbine engines, under USAF Contracts AF 33(616)-498, AF 33(616)-2659, AF 33(616)-3820, AF 33(616)-6232, and AF 33(616)-7223. The work performed under these programs has been described in several summary technical reports(1-5). Much of the basic approach employed in the previous programs can be extended to apply to the more sever requirements of the supersonic transport. Further, although certain additional test devices must be developed specifically for the current program, a large number of major test devices previously developed can, with suitable modifications or refinements, be utilized.

This progress report covers the work performed during the initial period of May 1, 1962 through July 31, 1962 under Contract AF 33(657)-9248.

During this period, the effort was directed mainly toward three areas. gear load-carrying capacity, bearing fatigue, and lubricant oxidation-corrosion.

In the gear load-carrying capacity phase, considerable dynamic calibration of the test equipment and exploratory testing of lubricants have been made at temperatures up to 500°F. The equipment used, the WADD high-temperature gear machine with the test gears maintained at the desired temperature by means of induction heating, was developed under Contract AF 33(616)-7223.

The bearing fatigue phase has been confined to design studies on a 3-ball/cone fatigue tester with a temperature capability of 800°F. Two alternative designs are being prepared. The final selection will be made on the basis of comparative study.

The lubricant oxidation-corrosion phase has encompassed further work on a 425°F oxidation-corrosion test procedure previously developed under Contract AF 33(616)-7223, design and construction of an oxidation-corrosion test apparatus with a temperature capability of 800°F, and exploratory testing of lubricants at 500°F

Detailed accounts of the work performed are presented in the succeeding chapters.

II. GEAR LOAD-CARRYING CAPACITY

A. General Remarks

The objectives of the gear load-carrying capacity phase are to develop apparatus and techniques for determining the load-carrying capacity of lubricants at bulk oil temperatures of 500° F and higher and to evaluate the gear load-carrying capacity performance of candidate lubricants under environmental conditions representative of Mach 3 class gas turbine engine designs.

Calibration of the load system of the WADD high-temperature gear machine was continued beyond the environmental requirements of the previous USAF contract (5) in order to insure reliable load-carrying capacity results at the higher test gear temperatures. During this period, satisfactory calibration results have been obtained at test gear temperatures up to 500° F. These results indicate that the diametral clearance currently being used for the support roller bearings of 0.0025 to 0.0035 in. is adequate for test gear temperatures in the 500° F region.

Preliminary gear load-carrying capacity investigations were made on selected lubricants at temperatures up to and including 500° F. The WADD high-temperature gear machine with SwRI design Nitralloy N steel test gears was used. The preliminary results obtained on the lubricants evaluated at 500° F indicate an increase in load-carrying capacity over that obtained at 400 and 425° F gear temperatures. The reasons for this unexpected trend are being investigated.

B. Development of Test [illegible] and Technique

1 WADD High-Temperature Gear Machine

The experiments reported herein were conducted using two WADD high-temperature gear machines developed under Contract AF 33(616)-7223(5). A cross section of this machine is shown in Figure 1. Its operating principle is identical to that of the standard Ryder gear machine(6). However, improvements in materials and design were made to extend the operating capability of the machine. Tests have shown that this machine is capable of operating at speeds up to 30, 000 rpm and test gear temperatures up to 800° F. The WADD high-temperature gear machine differs from the standard Ryder gear machine in that each shaft is supported by two double-row roller bearings instead of three journal bearings as used on the standard machine. The load chamber is located on the end of the driven shaft.

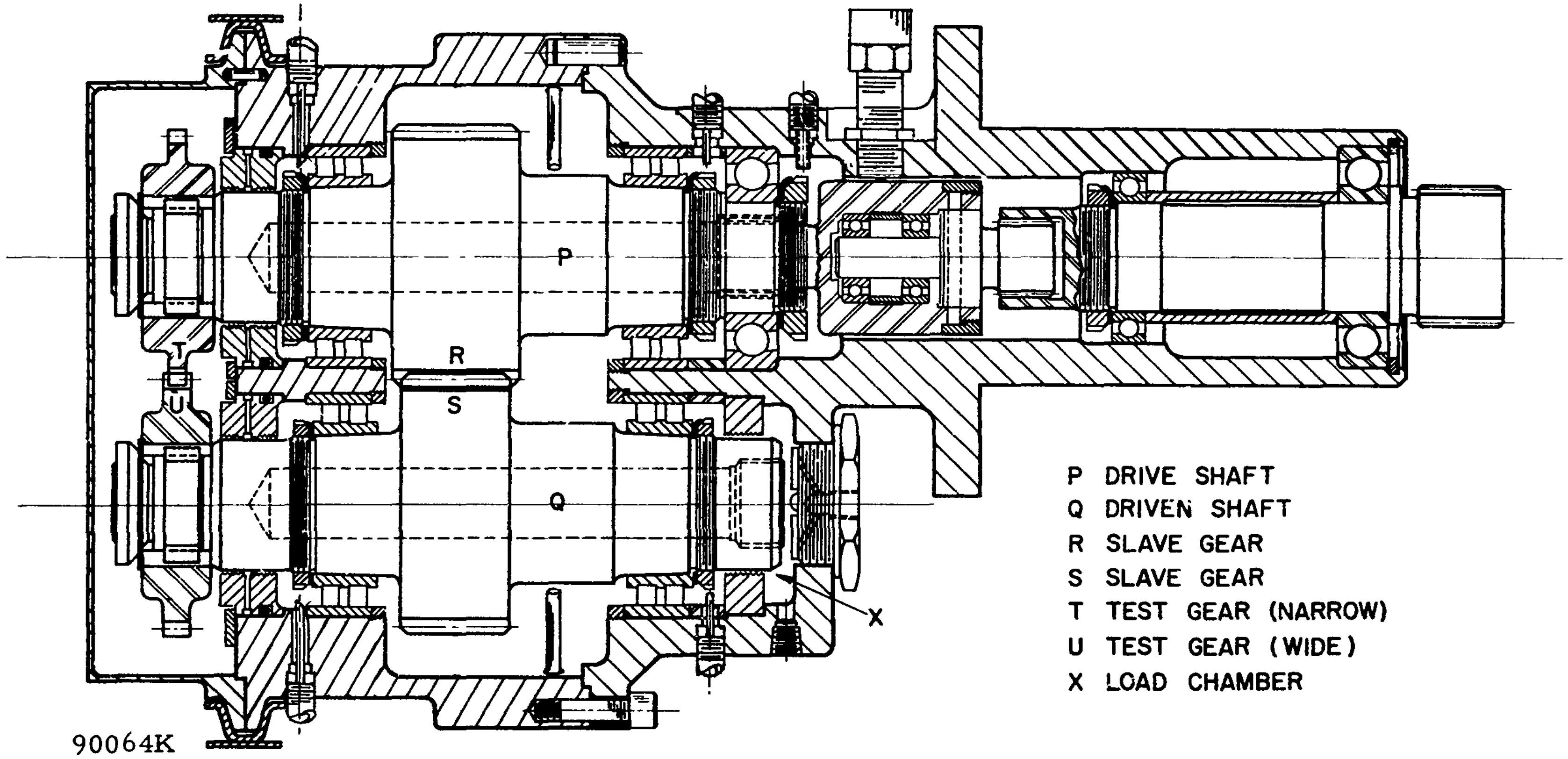

P
R
S
Q
T
U
X
P DRIVE SHAFT
Q DRIVEN SHAFT
R SLAVE GEAR
S SLAVE GEAR
T TEST GEAR (NARROW)
U TEST GEAR (WIDE)
X LOAD CHAMBER
90064K

FIGURE 1. CROSS SECTION OF WADD HIGH-TEMPERATURE GEAR MACHINE

Screw-thread type nonrubbing seals, rather than elastomer seals, are used to separate the test oil and support oil chambers. The case is made of tool steel to improve structural stability at elevated temperatures The WADD high-temperature gear machine with high-temperature test gears and the induction heating coil installed is shown in Figure 2. The induction heating coil is normally rigidly attached to the test end cover and is removed with the cover each time the cover is removed

In the operation of the gear machine, the test gear tooth load is obtained by the application of controlled hydraulic load in the load chamber, X (Fig. 1). This hydraulic load causes a slight axial movement of one shaft relative to the other and is converted into a tangential load on the replaceable spur test gears, T and U, through the action of the integral helical slave gears, R and S. The test gear tooth load is computed from the applied hydraulic load and the geometry of the load system

The hydraulic load (or load oil pressure) is controlled automatically by means of a pneumatic controller-recorder. This system affords automatic setting and control of the load oil pressure to within ±0.25 psi over a range of 0 to 120 psig. This corresponds to a sensitivity of approximately ± 10 lb/in. for tooth loads ranging from 0 to 5600 lb/in., which is the load range of the machine. The rate of load application is constant for any one load setting and is independent of the operator.

The WADD high-temperature gear machines are driven by standard Erdco 50-hp drive units which were modified earlier(4) to permit operation of the gear machines at speeds up to 30,000 rpm through a step-up gear ratio of 9.25:1.

2. Test Oil Systems

For high-temperature gear tests, where some degree of test oil deterioration during test appears to be unavoidable and must therefore be minimized or controlled as much as possible, it was felt that direct contact of the test oil with a high-wattage immersion heater, as used in the standard Erdco test oil system, should be avoided. With this in mind, two test oil systems, one a "two-gallon" system and the other a "1/2-liter" system, were previously designed and fabricated under Contract AF 33(616)-7223. The two-gallon test oil system was designed to use the same quantity of test oil as the standard Erdco test oil system. However, the 1/2-liter test oil system, designed at a somewhat later date, has been recently used to a much greater extent, due to the smaller amounts of limited-quantity, expensive lubricants required.

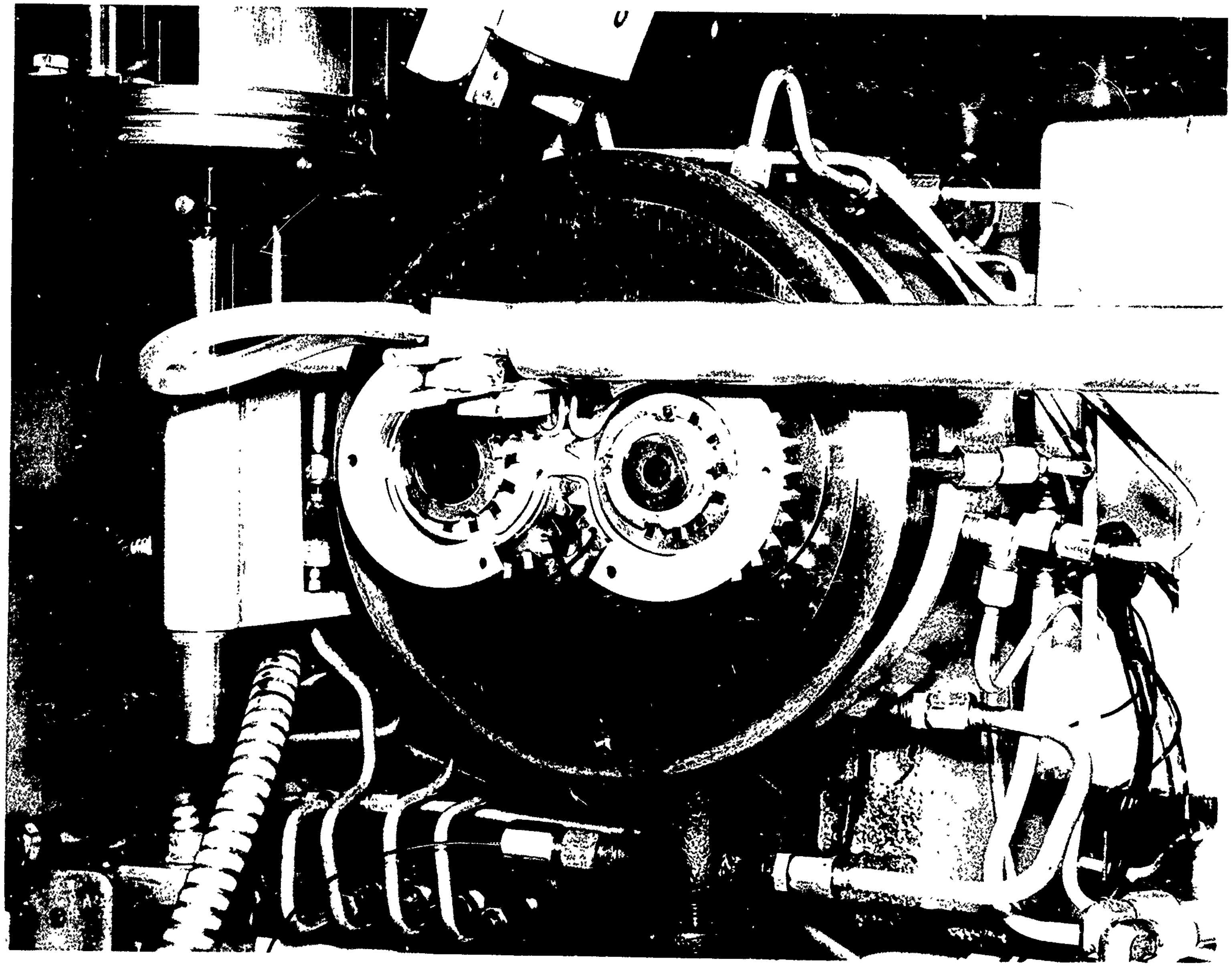


FIGURE 2. PHOTOGRAPH OF WADD HIGH-TEMPERATURE GEAR MACHINE WITH HIGH-TEMPERATURE TEST GEARS AND INDUCTION HEATING COIL INSTALLED

Schematic diagrams and photographs of the two test oil systems are shown in Figures 3, 4, 5, and 6 The sumps of both systems are constructed of stainless steel and are double walled. The two-gallon system has an insulating material between the walls. Because heat loss is critical with the smaller volume system, a low wattage band heater is located in the space between the inner and outer wall.

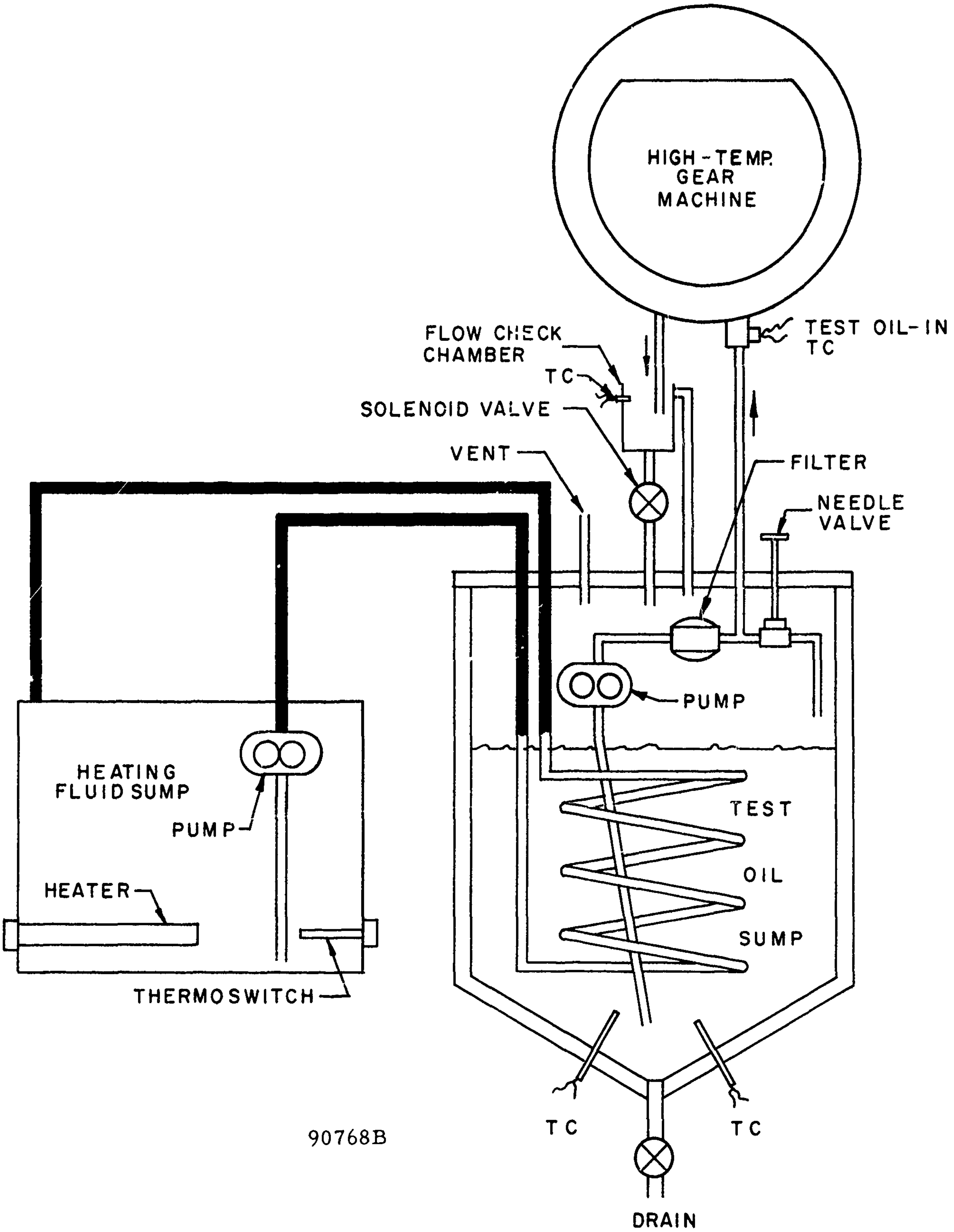
These systems are capable of being operated at bulk oil temperatures up to and including 400°F. The test oil is heated by means of a heat exchanger placed inside the sump By this means, excessive localized heating of the test oil is avoided. The accessories, with exception of the pressure pump motor, are located inside the sump, thereby eliminating considerable heat loss to the ambient. The lines to and from the gear machine are made very short, again in an effort to minimize heat loss. With these precautions, the temperature of the test oil in the sump need be only a few degrees higher than that entering the machine, and a minimum of deterioration of the test oil is obtained during a test.

3. Standard 165°F Support Oil System

With induction heating to heat the test gears in the high-temperature load-carrying capacity studies, the standard Erdco support oil system(6) is used to lubricate the support section of the high-temperature gear machine and to supply load oil pressure. Apart from the lubricating function, the 165°F support oil is also used as a control coolant in maintaining the test gear temperature by carrying away excess heat from the gear machine bearings and shafts.

4. High-Temperature Test Gears

For the work described herein, special test gears made of Nitralloy N steel were used. These special gears have the same principal dimensions as the standard Ryder test gears(6) but conform to SwRI design with respect to the chordal thickness and the tooth width of the wide gear. A modification was made to the design of the wide test gear to increase the backlash of the gear set. This increased backlash was determined to be necessary for tests to be conducted at gear temperatures above 400°F. Details of this modification are described in a subsequent section of this report. The principal dimensions of the high-temperature test gears are shown in comparison with those of the standard Ryder test gears in Table 1. In Table 1, the case hardness is given in Rockwell 15 N units and the core hardness is given in Rockwell C units, the usual units of these measurements.


HIGH-TEMP. GEAR MACHINE
FLOW CHECK CHAMBER
TC
SOLENOID VALVE
VENT
TEST OIL-IN TC
FILTER
NEEDLE VALVE
PUMP
HEATING FLUID SUMP
PUMP
HEATER
THERMOSWITCH
TEST OIL SUMP
TC
TC
DRAIN

90768B

FIGURE 3. SCHEMATIC DIAGRAM OF TWO-GALLON HIGH-TEMPERATURE TEST OIL SYSTEM

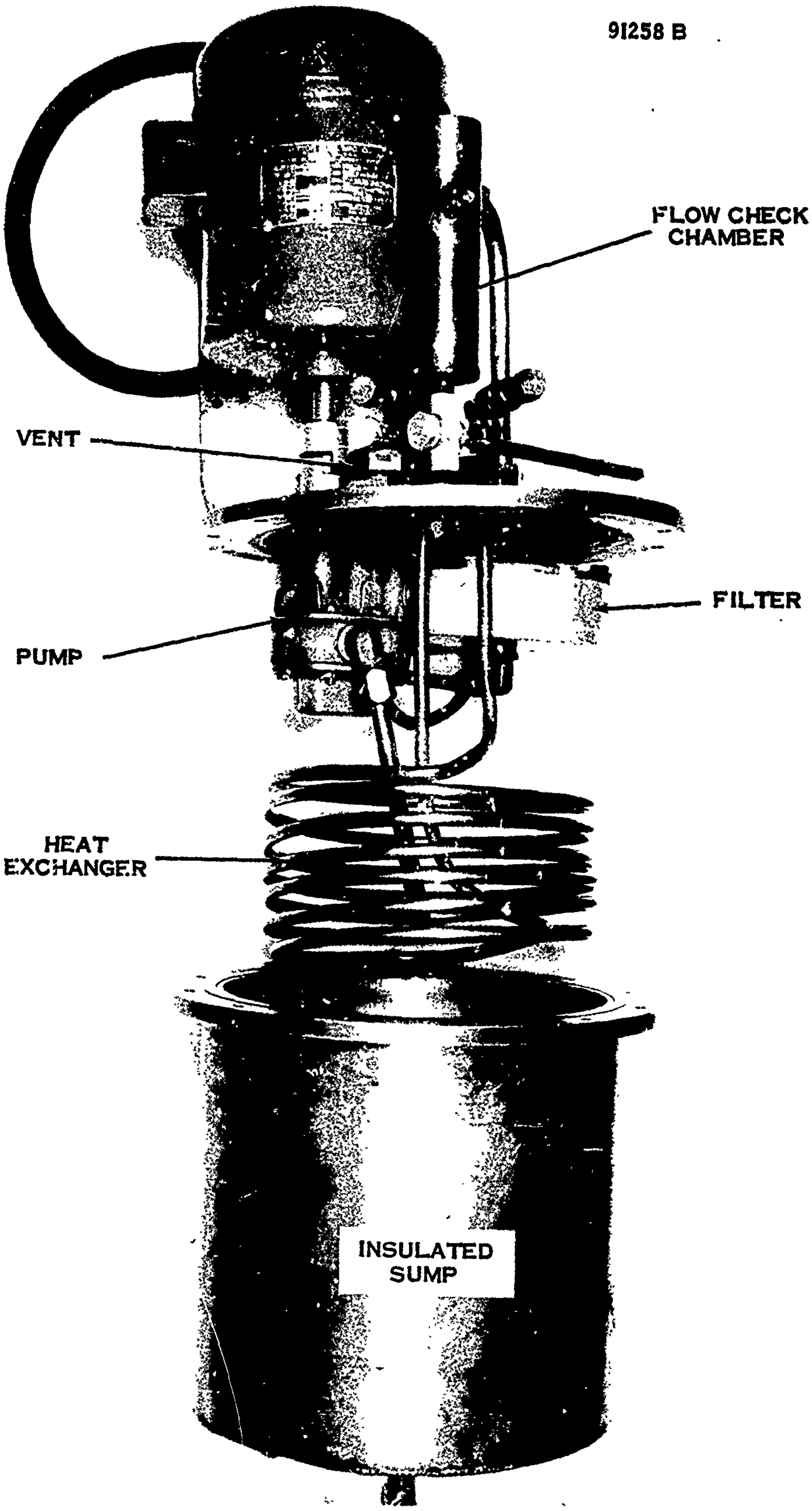

91258 B
FLOW CHECK CHAMBER
VENT
FILTER
PUMP
HEAT EXCHANGER
INSULATED SUMP

FIGURE 4. PHOTOGRAPH OF TWO-GALLON HIGH-TEMPERATURE TEST OIL SYSTEM

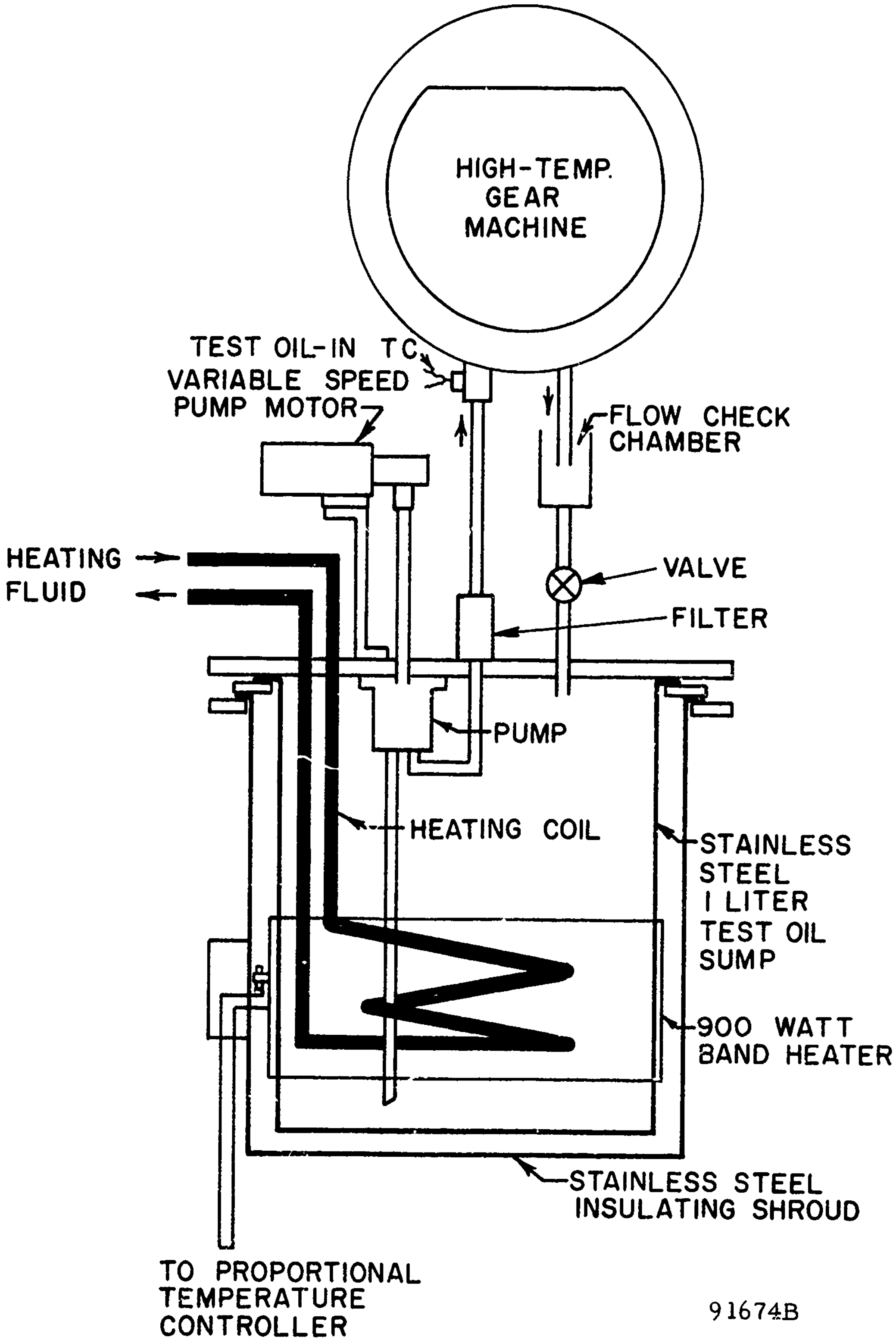

HIGH-TEMP. GEAR MACHINE
TEST OIL-IN TC
VARIABLE SPEED PUMP MOTOR
FLOW CHECK CHAMBER
HEATING FLUID
VALVE
FILTER
PUMP
HEATING COIL
STAINLESS STEEL I LITER TEST OIL SUMP
900 WATT BAND HEATER
STAINLESS STEEL INSULATING SHROUD
TO PROPORTIONAL TEMPERATURE CONTROLLER
91674B

FIGURE 5. SCHEMATIC DIAGRAM OF HALF-LITER TEST OIL SYSTEM

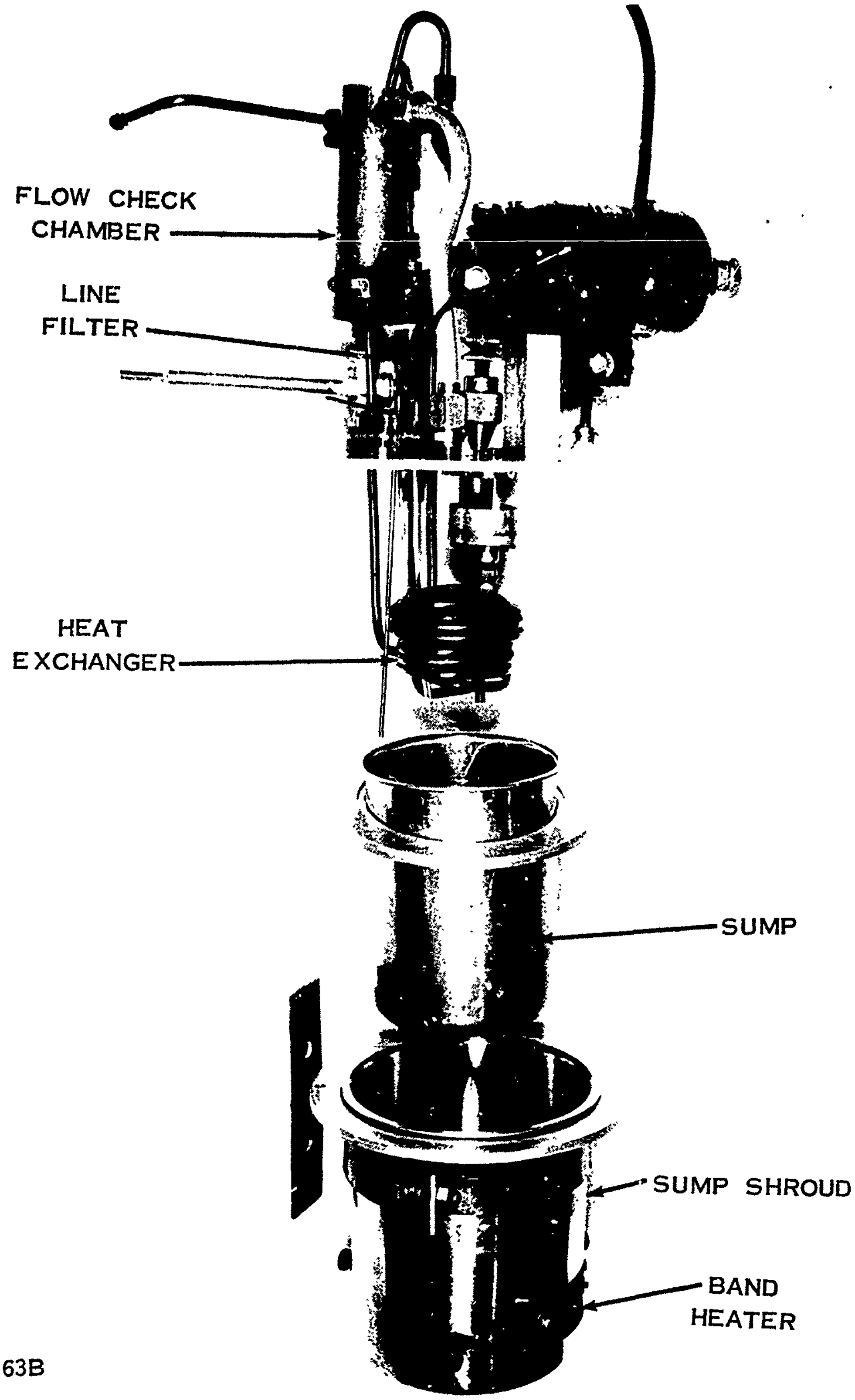

FLOW CHECK CHAMBER
LINE FILTER
HEAT EXCHANGER
SUMP
SUMP SHROUD
BAND HEATER
91863B

FIGURE 6. PHOTOGRAPH OF HALF-LITER TEST OIL SYSTEM

TABLE 1. COMPARISON OF PRINCIPAL DIMENSIONS OF STANDARD RYDER TEST GEARS WITH HIGH-TEMPERATURE TEST GEARS

	Standard Ryder Test Gears	High-Temperature Test Gears
Pitch Diameter, in.	3.500	3.500
Face Width, Narrow Gear, in.	0.250	0.250
Face Width, Wide Gear, in.	0.937	0.375
Number of Teeth	28	28
Diametral Pitch	8	8
Pressure Angle, degree	22.5	22.5
Tip Relief	None	None
Material	AMS-6260	Nitralloy N
Case Hardness, Rockwell 15N	90-92	90-92
Case Thickness, in.	0.025-0.040	0.018-0.024
Core Hardness, Rockwell C	30-40	30-40
Surface Finish, rms, in.	$20\text{-}35 \times 10^{-6}$	$20\text{-}35 \times 10^{-6}$
Backlash, in.	0.002-0.006	0.011-0.014

5. Induction Heating of Test Gears

In the induction heating of the test gears, the induction coil is placed closely and accurately with respect to spacing around the hub of both the narrow and wide test gears A photograph of one of the induction heating coils used is shown in Figure 2. With the gears turning in the induction field, the heat is evenly distributed from the hub outward to the gear teeth. This insures that the heat distribution and temperature are very nearly equal in both the narrow and wide gears which further insures that the lubricant in the gear mesh is subjected to nearly equal temperature conditions.

6. Temperature Measurement of Test Gears

The temperature of the test gear is measured by an industrial infrared radiometer. The radiometer measures the infrared radiation from the test gear. This measurement is related to temperature by means of calibration against thermocouple readings. These data are then plotted and a radiometer output versus temperature curve is obtained. It is from this curve that the gear temperature is then determined. This method was developed and calibration curves obtained under Contract AF 33(616)-7223.(5) The system of gear temperature measurement and control is shown in Figures 7 and 8.

The gear-blank temperature measurement is made at a point on the web of the narrow gear near the mesh of the test gears. Ideally, the temperature measurement and control should be at the mesh of the gear teeth, but, since the gear teeth undergo changes during a test from the standpoint of infrared emissivity, it was decided that the gear web was the next most logical measuring point. Since the observation of the gear web is continuous while the gear is turning, it is expected that the emissivity factor will be very nearly constant, thereby insuring that little error in temperature measurement from the standpoint of emissivity will be obtained. To further insure a constant emissivity-temperature relationship during a test, it is necessary to obtain approximate black-body radiation from the test gear web. This is obtained by making the gear web black in color by electroplating the web of the gear with black chromium.

A calibration apparatus is located near the machine such that the output of the radiometer can be checked at any time it is felt necessary. This apparatus consists of two steel blocks so machined that when a gear is placed between them a form fit on the gear is obtained. The apparatus, shown in Figure 9, is heated by cartridge heaters placed in the steel blocks as shown. The radiometer is focused on the plated portion of the gear web

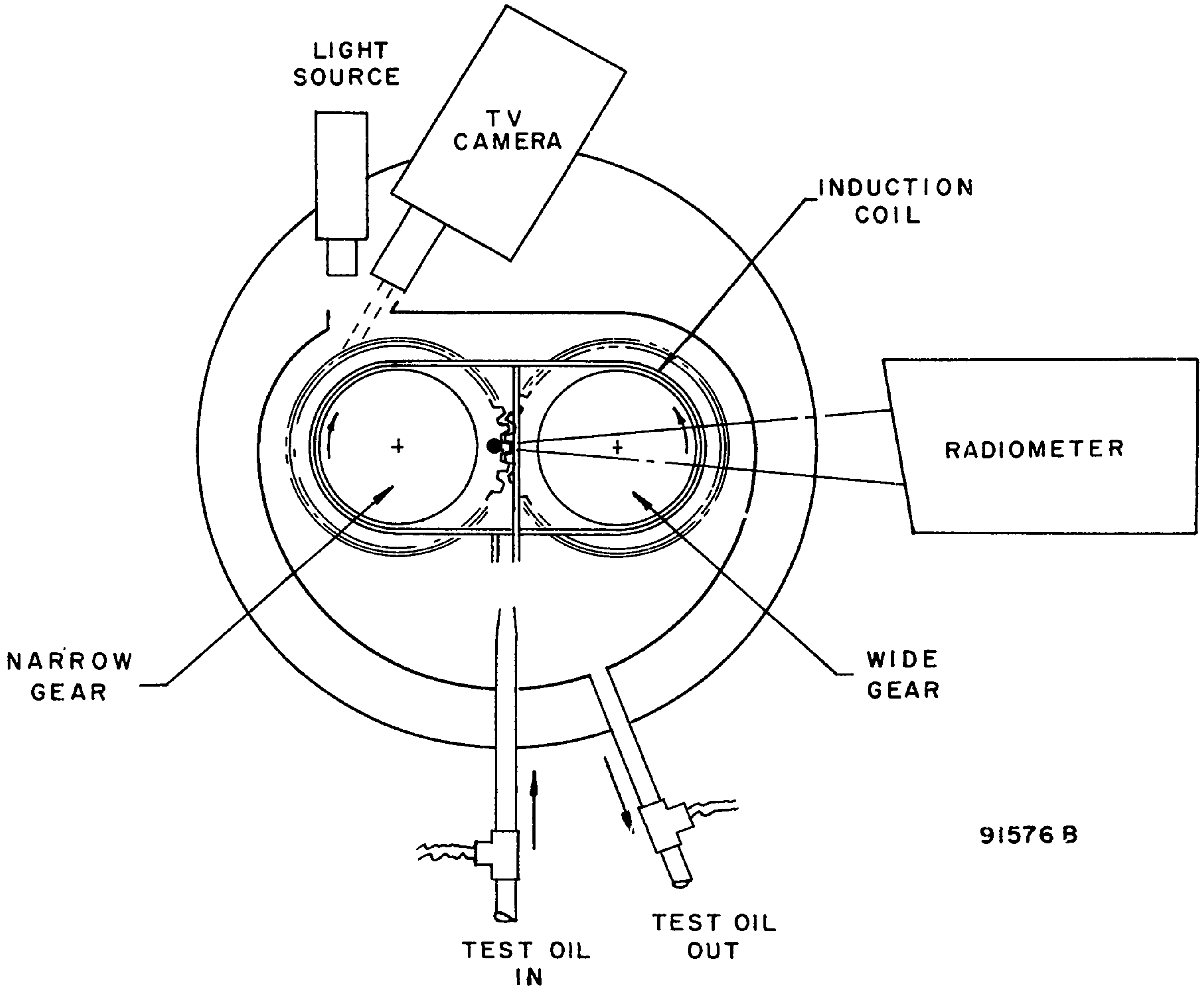

LIGHT SOURCE
TV CAMERA
INDUCTION COIL
RADIOMETER
NARROW GEAR
WIDE GEAR
91576 B
TEST OIL IN
TEST OIL OUT

FIGURE 7. INDUCTION HEATING AND GEAR-WEB TEMPERATURE MEASUREMENT

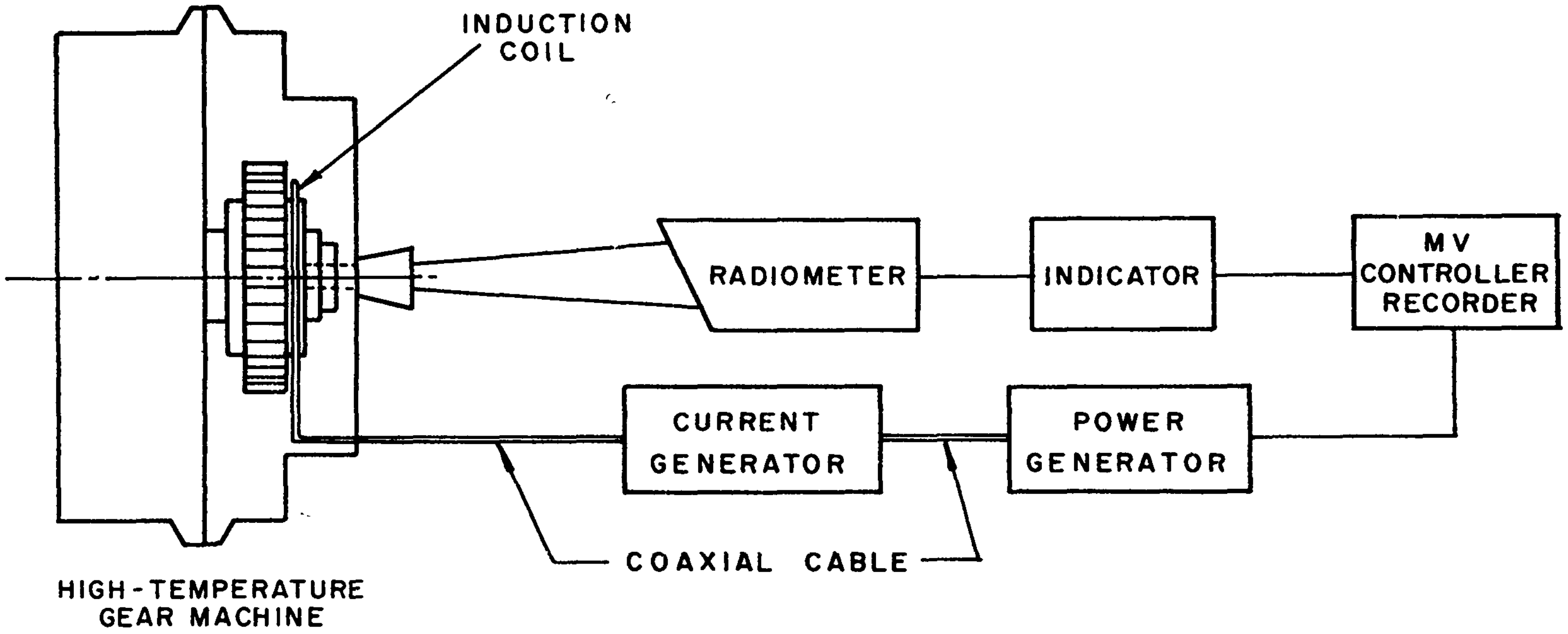

INDUCTION COIL
RADIOMETER
INDICATOR
MV CONTROLLER RECORDER
CURRENT GENERATOR
POWER GENERATOR
COAXIAL CABLE
HIGH-TEMPERATURE GEAR MACHINE

FIGURE 8. INDUCTION HEATING CONTROL SYSTEM

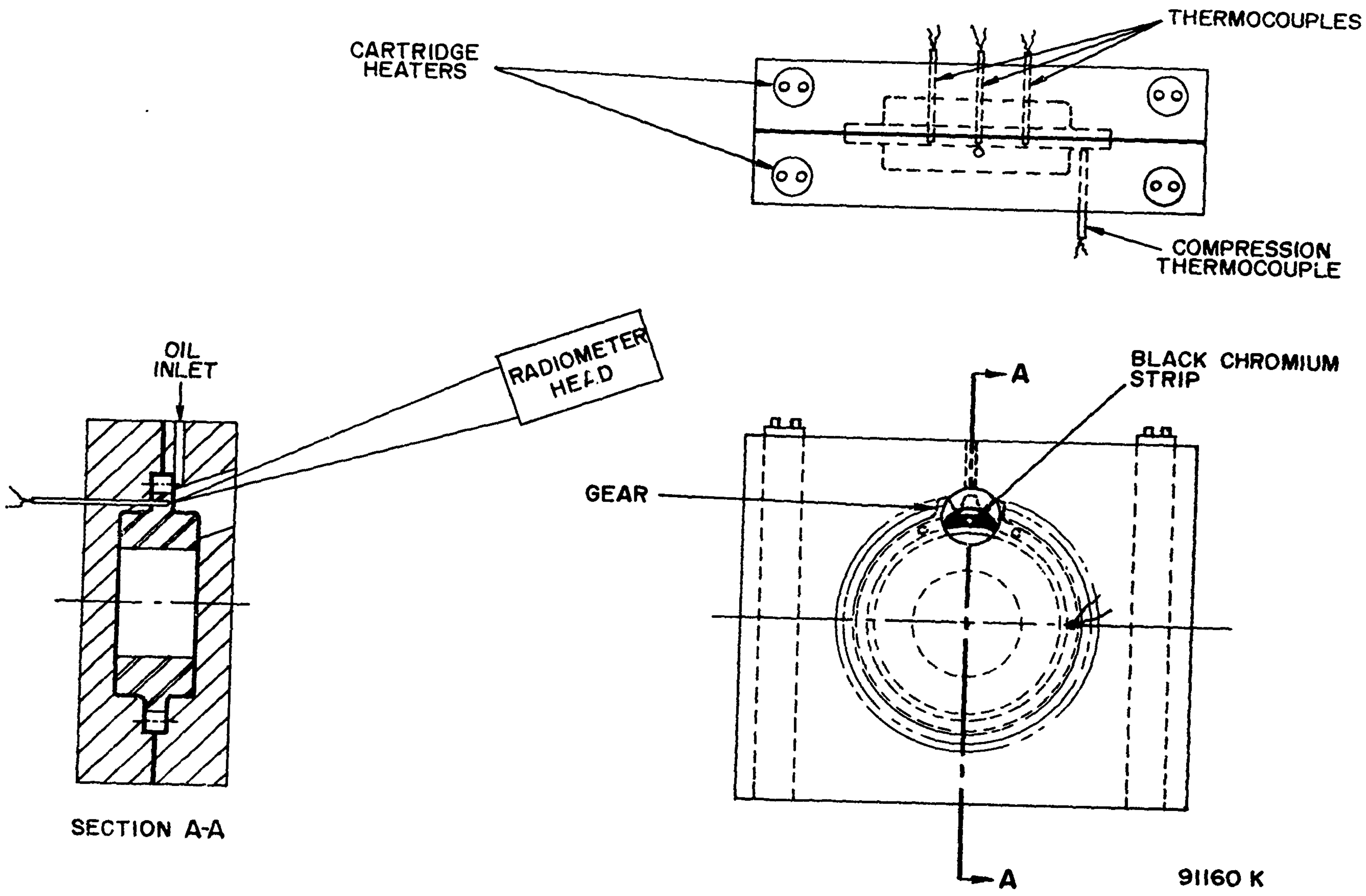

CARTRIDGE HEATERS
THERMOCOUPLES
COMPRESSION THERMOCOUPLE
OIL INLET
RADIOMETER HEAD
SECTION A-A
BLACK CHROMIUM STRIP
GEAR
A
A
91160 K

FIGURE 9. RADIOMETER CALIBRATION APPARATUS

through a hole in the block. Thermocouples are fitted into the web of the gear from the side opposite the point at which the radiometer is focused, and to a depth such that they are within 1/32 in. of the face of the web. With this apparatus, thermocouple-radiometer output may be checked over the desired temperature range.

A more rapid but somewhat less accurate check may be made of the radiometer by painting the gear teeth of a used test gear with temperature indicating paints. The gear is then placed on the machine and, with the induction heating coil in place, the gear is heated until the paints melt. The radiometer output is noted at the melting point of each of the paints. These paints are available in 50°F melting-point increments from 400 to 1000°F.

7. Closed-Circuit Television for Gear Inspection

To insure safety of the operating personnel from exposure to high-temperature parts and toxic fumes, it is now standard practice at SwRI to locate all high-temperature test rigs in individual test cells that are well ventilated, and to perform as many of the controlling and inspection operations as possible from outside the test cells. The closed-circuit television method for gear inspection, developed previously(5), has been adopted for general use in gear lubrication experiments at SwRI, and approximately 250 scuff ratings have been obtained with this method. During a number of such tests, satisfactory checks of the television ratings with the standard visual-microscopic ratings were obtained.

C. Operating Procedures

1. High-Temperature Load-Carrying Capacity

The procedure used in the high-temperature load-carrying capacity studies differs only slightly from Federal Test Method 6508 in that a different machine (WADD high-temperature gear machine), special test gears, and induction heating of the test gears are used. A comparison of the two test methods is shown in Table 2.

The specific WADD high-temperature gear machine operational procedure is as follows: A warm-up period is allowed with all systems functioning with the exception of the drive and the induction heating systems. After attaining the desired test oil and support oil temperature equilibrium, the drive system is activated and the machine is driven at 10,000 rpm. The induction heat control system is set at the desired temperature and the test gear temperature is obtained and controlled automatically The time required to heat the test gears to 500°F is approximately two minutes.

TABLE 2. COMPARISON OF LOAD-CARRYING CAPACITY TEST METHODS

	Federal Test Method 6508	Methods Used in Present Program	
		165°F Test	≥ 400°F Test
Test Machine	Erdco-Ryder gear machine	WADD high-temperature gear machine	WADD high-temperature gear machine
Test Gears	Ryder test gears	Special Nitralloy N test gears	Special Nitralloy N test gears
Operating Conditions			
Test gear speed, rpm	10,000 ± 10	10,000 ± 100	10,000 ± 100
Test oil flow rate, ml/min (exit lubrication)	270 ± 5	270 ± 5	270 ± 5
Test oil-in temperature, °F	165 ± 5	165 ± 5	400 ± 5
Support oil-in temperature	165 ± 5	165 ± 5	165 ± 10
Test Gear Temperature	Not controlled	Not controlled	Controlled at required test temperature
Method of Loading			
Increment steps in tooth load (corresponding to 5-psi steps in load oil pressure), lb/in.	370	230	230
Duration of load-increment steps, min	10	10	10
Criterion of Lubricant Rating	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed	Tooth load at which 22.5% of working tooth area is scuffed

The desired load is next set into the load system which automatically loads and controls the load on the gear teeth. After the load is obtained, the interval timer is set for the standard load duration time of ten minutes. Five minutes after start of the load duration, all temperatures and pressures are noted and recorded. At the end of the ten-minute period, the timer shuts down the drive. The operator then, in reverse order to that given above, turns off the load and induction heat to the gears. The machine is then stopped, and the narrow gear teeth are inspected. The procedure is then repeated for the next higher load. The test is terminated at least one load step after an average of 22.5 percent scuff is obtained on the narrow gear.

2. Gear Machine Calibration

The procedure used in the calibration of the WADD high-temperature gear machine is the same as that used in the high-temperature load-carrying capacity procedure. The only exception is that the time at temperature equilibrium is extended so as to obtain three points at strain equilibrium. This is necessary because the sensitivity of the strain output to temperature variation is approximately 5 μin./in./°F. The strain data are recorded at each gear temperature and load level. These data are plotted versus load oil pressure or shaft torque at each gear temperature. The load deviation in then determined by a comparison of the strain-load curve with the static, dead-weight load curve.

D. Calibration of the WADD High-Temperature Gear Machine

1. Apparatus and Technique

In both the standard Ryder gear machine and the WADD high-temperature gear machine, load on the gear teeth is obtained by the application of an axial hydraulic pressure on the load shafts, which is converted into load on the gear teeth through the action of the helical slave gears made integral with the shafts. The tooth load is computed from the axial hydraulic pressure applied and the geometry of the load system (neglecting friction). In an effort to establish the validity of the computed relationship, a program was initiated under AF 33(616)-7223 to calibrate the load system of the WADD high-temperature gear machine.(5)

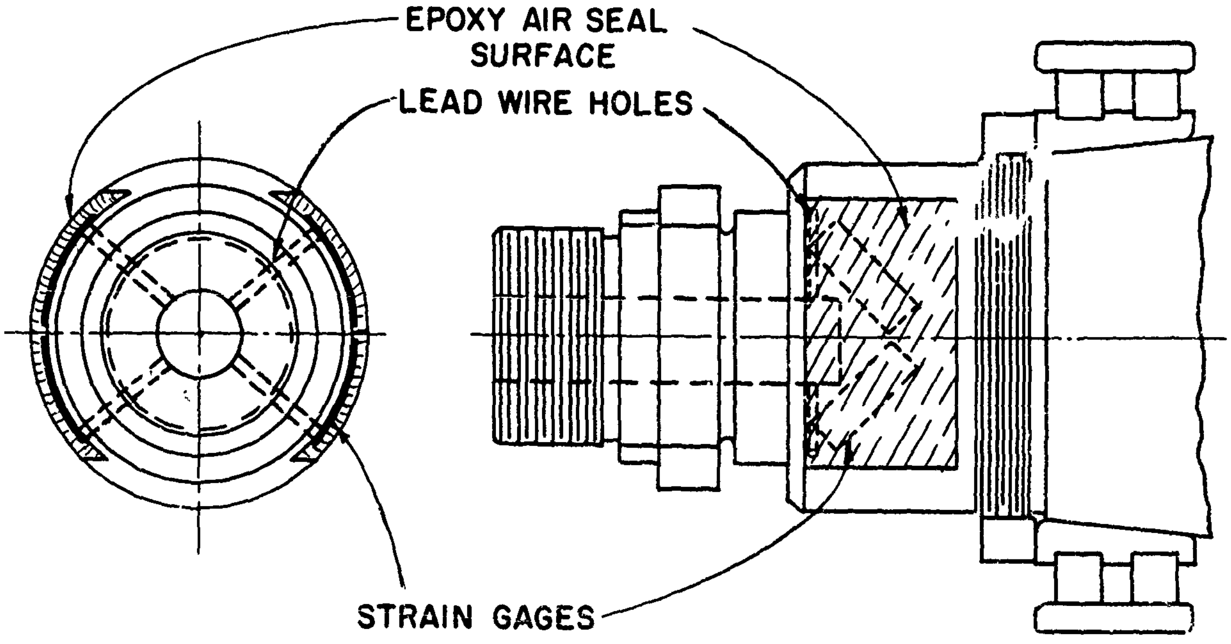
A number of different approaches were considered as a means of obtaining a meaningful calibration of the machine. Of the several approaches considered, it was decided that the calibration would be made by taking torque measurements of the gear machine drive shaft in the area of the screw thread nonrubbing air seal. This method presented several advantages in that a special gear would not be required, any test gear might be used or changed as necessary, the strain gage service would be less severe and could be air-cooled as necessary, and the changes to the drive shaft to accommodate the strain gages would be minor and would not affect the shaft with respect to its use in normal load-carrying capacity testing.

In developing the technique and method of applying the gages to the machine shaft, a considerable amount of time and effort went into trials and errors in the selection of an applicable strain gage and mounting technique from all those recommended. The main difficulty encountered in most instances was the bonding of the gages to the shaft such that the bond would withstand the extremely adverse conditions of temperature and the very high strain frequencies which exist during dynamic operation. The mounting technique now in use appears to be satisfactory from the standpoint of many hours of trouble-free operation.

The load system calibration apparatus consists of four uniaxial etched-foil bakelite-backed FAB-12-12 strain gages, a four-channel mercury slip ring assembly, and a strain-gage strain indicator.

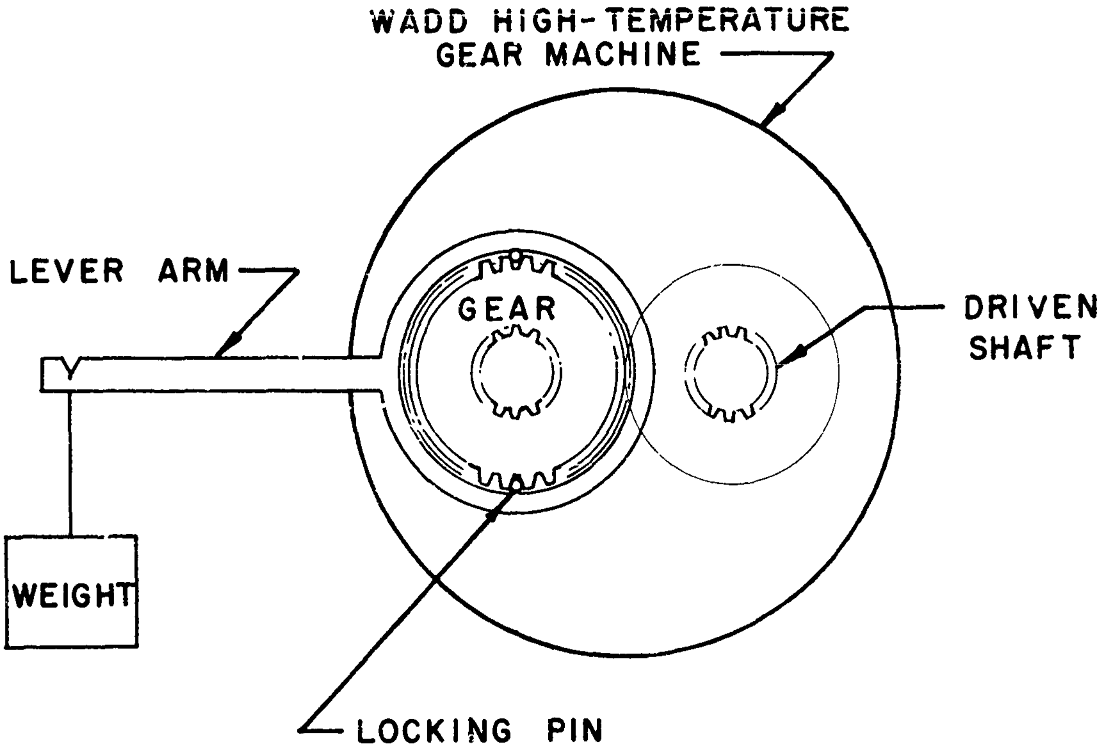
Two pairs of strain gages are mounted in a milled-out area 180° apart on the drive shaft of the gear machine in the area of the screw thread nonrubbing air seal, as shown in Figure 10 The strain gages are mounted in the recessed area with a 400°F epoxy cement, and the remaining void is filled with the same cement containing an asbestos binding fiber. The entire shaft is then thermal cycled in various increments of temperature to 500°F over a period of 24 hours. The protruding and irregular excess epoxy is then machined to the dimension of the air seal surface of the shaft. After stress relieving to 2000 in.-lb of torque in increments of 200 in.-lb, the system is ready for dynamic operation.

The static, dead-weight load system used in the calibration work is self-explanatory and is shown in Figure 11. A schematic diagram of the full bridge strain-gage system is shown in Figure 12.


EPOXY AIR SEAL SURFACE
LEAD WIRE HOLES
STRAIN GAGES

91829 B

FIGURE 10. STRAIN GAGE INSTALLATION TO ALLOW STANDARD NONRUBBING SEAL TO BE USED


WADD HIGH-TEMPERATURE GEAR MACHINE
LEVER ARM
GEAR
DRIVEN SHAFT
WEIGHT
LOCKING PIN

91729 B

FIGURE 11. DEAD-WEIGHT LOAD ASSEMBLY

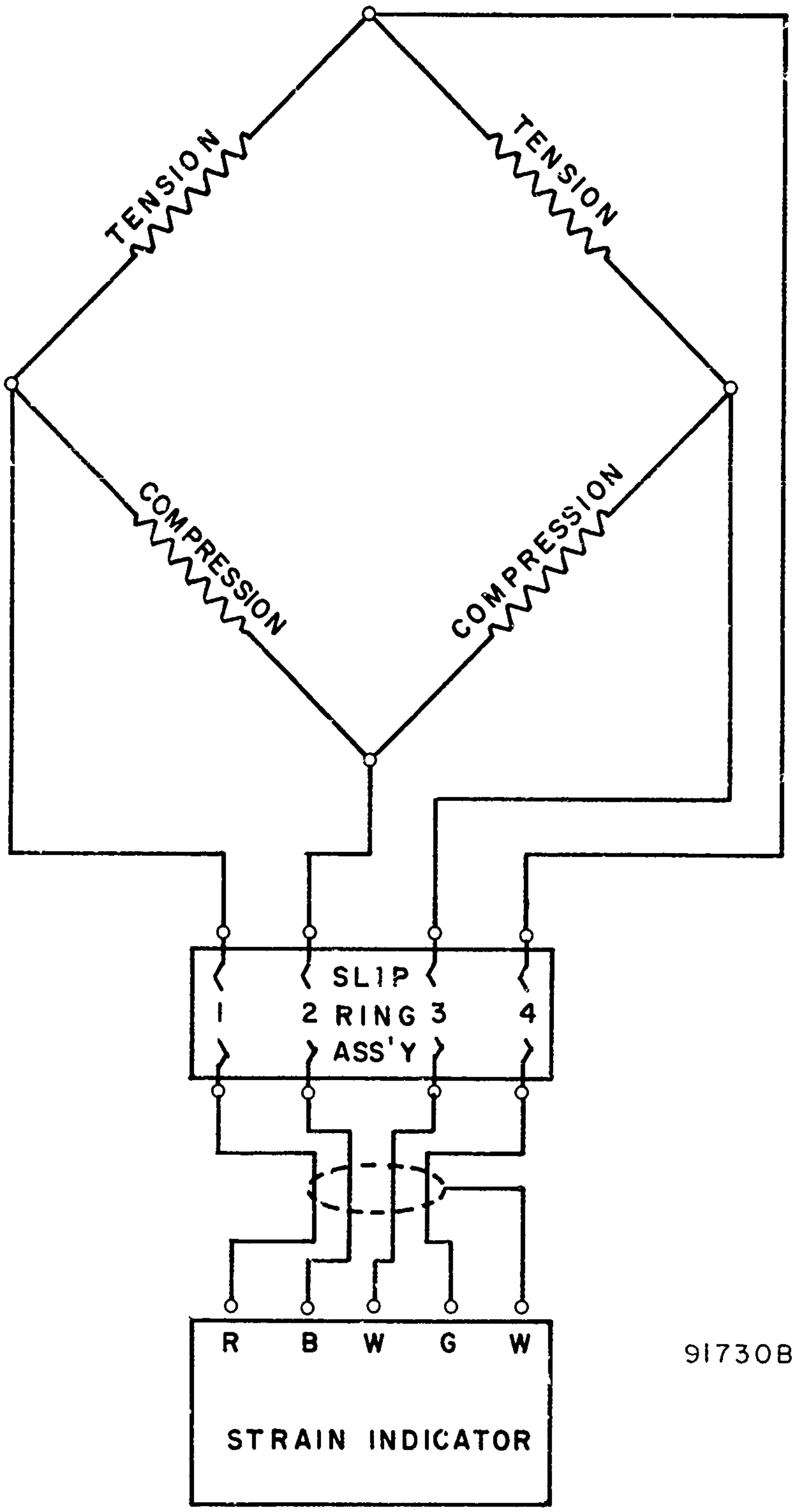

TENSION
TENSION
COMPRESSION
COMPRESSION
1
2
3
4
SLIP RING ASS'Y
R
B
W
G
W
STRAIN INDICATOR
91730B

FIGURE 12. SCHEMATIC DIAGRAM OF FULL BRIDGE STRAIN-GAGE SYSTEM

2. Discussion of Calibration Results

During the dynamic load system calibration, carried out earlier(5), there were indications that the standard diametral clearance (0.0005 in.) of the support roller bearings in the WADD high-temperature gear machine was probably inadequate for the 400°F conventional load-carrying capacity tests (10,000 rpm, 400°F test oil and support oil temperatures). This conclusion was reached because the calibration results had a greater scatter for the conventional 400°F test conditions than for the conventional 165°F conditions (10,000 rpm, 165°F test oil and support oil temperature). Although no difficulties were experienced with the 400°F induction heating load-carrying capacity tests (10,000 rpm, 165°F test oil and support oil temperatures, 400°F induction heated gear temperature), it was reasoned that the support roller bearing clearance was on the low side if the induction-heating tests were to be extended to gear temperatures substantially beyond 400°F. Accordingly, it was decided that studies should be made to establish the bearing clearance required to give satisfactory machine operation and repeatable load system performance over as wide a range of conditions as possible.

In these early studies, it was shown that with a diametral clearance of 0.005 in., a 0.0045-in. increase over the standard clearance of 0.0005 in., the dynamic calibration results for the 400°F conventional test conditions were comparable to those for the 165°F conventional test conditions. It was therefore decided that the bearing clearances for drastically different test conditions should be considered separately, and that an effort should be made to use a bearing clearance no more than needed for the particular set of test conditions. Further, since the current program is concerned primarily with operation at 10,000 rpm and gear temperatures above 400°F, the effort should primarily be directed toward this application.

With the above considerations in mind, dynamic load system calibration was made with a diametral support roller bearing clearance of 0.0025 in., at 10,000 rpm and 165°F test oil and support oil temperatures. Bearings with 0.0025-in. diametral clearance were obtained by grinding the inner surface of the outer race of the standard bearings. The results obtained are shown in Figures 13 and 14. Comparison of these figures with Figures 15 and 16 shows the calibration results for 0.0025-in. diametral bearing clearance are comparable to those for 0.005-in. clearance.

During the reporting period, calibration studies were made at 400 and 500°F test gear temperature conditions (10,000 rpm, 165°F support oil temperature, 400°F test-oil-in temperature, 400 and 500°F

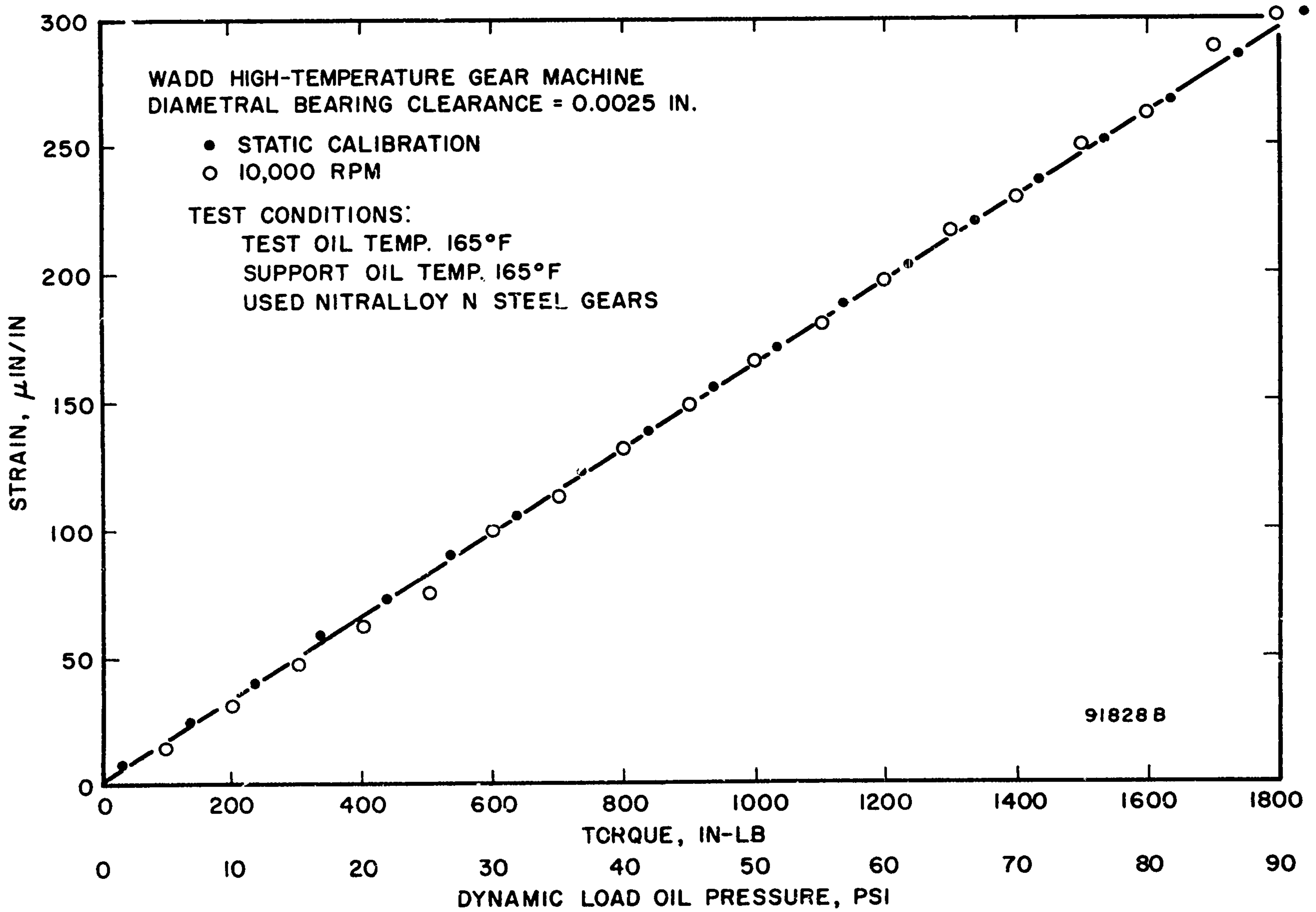


FIGURE 13. COMPARISON OF STATIC AND DYNAMIC CALIBRATION CURVES AT 165°F WITH 0.0025-IN DIAMETRAL SUPPORT BEARING CLEARANCE

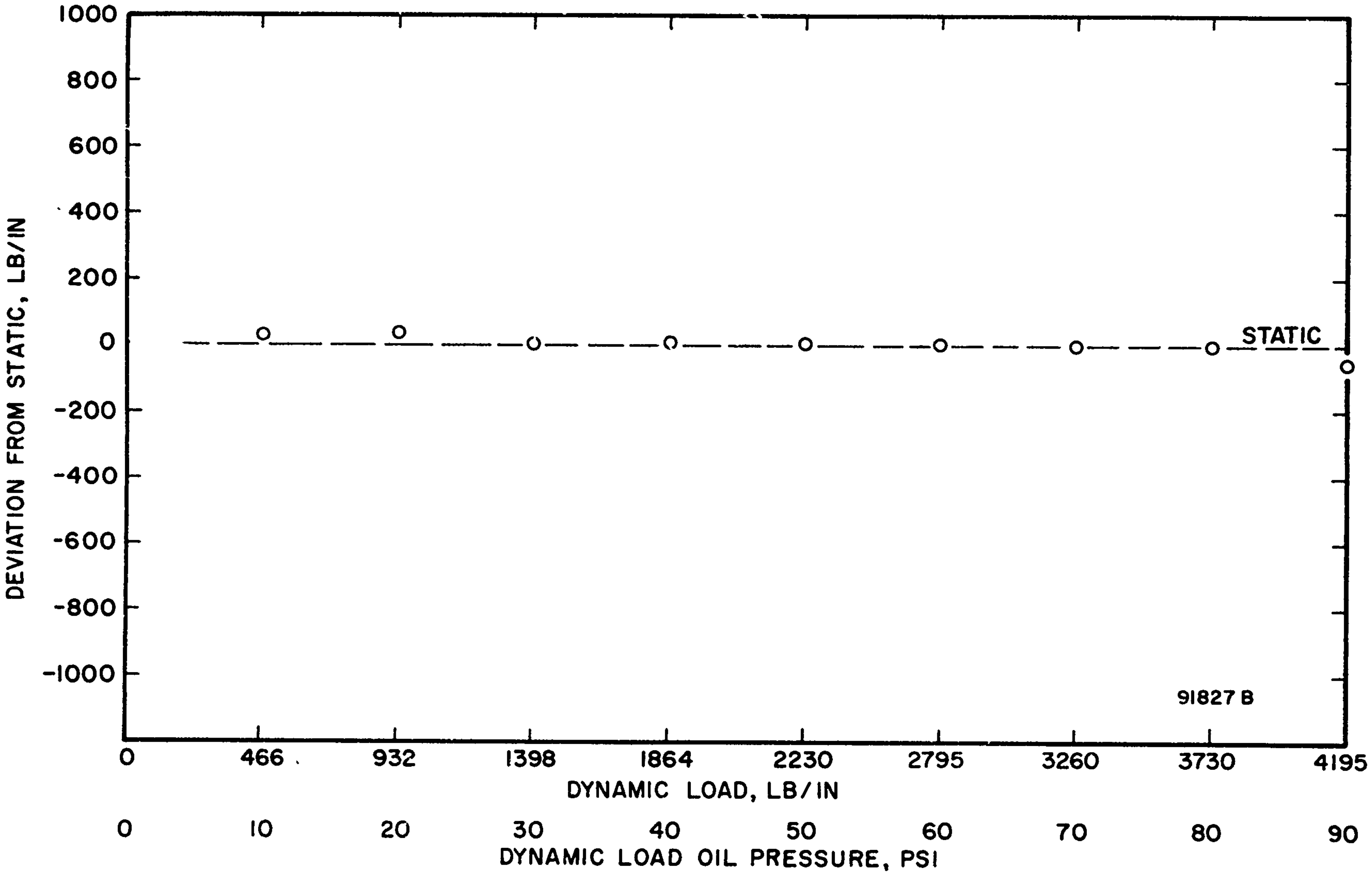


FIGURE 14. GEAR TOOTH LOAD DEVIATION BETWEEN STATIC AND DYNAMIC CALIBRATION WITH 0.0025-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

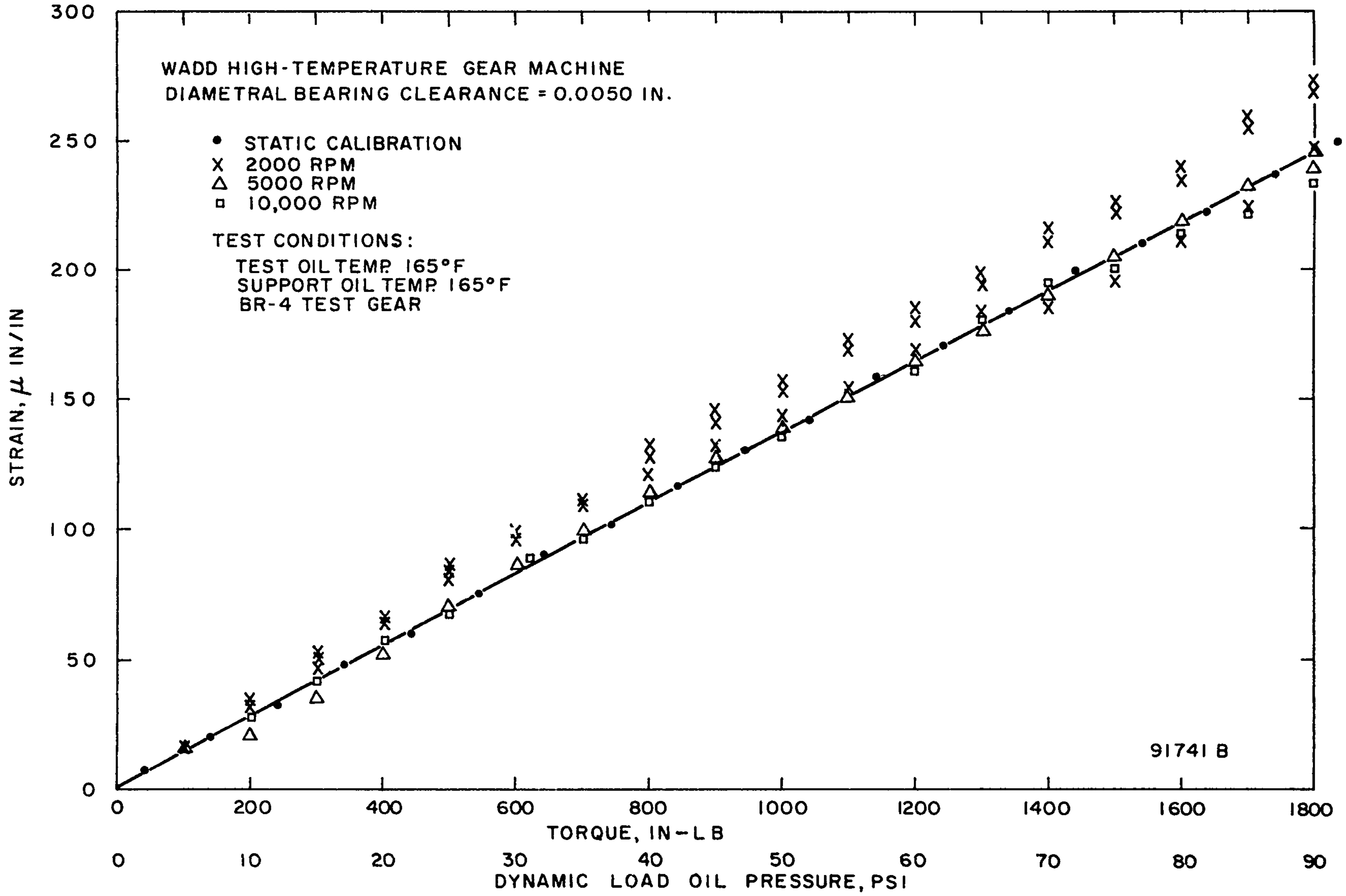


FIGURE 15. COMPARISON OF STATIC AND DYNAMIC CALIBRATION CURVES AT 165°F WITH 0.005-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

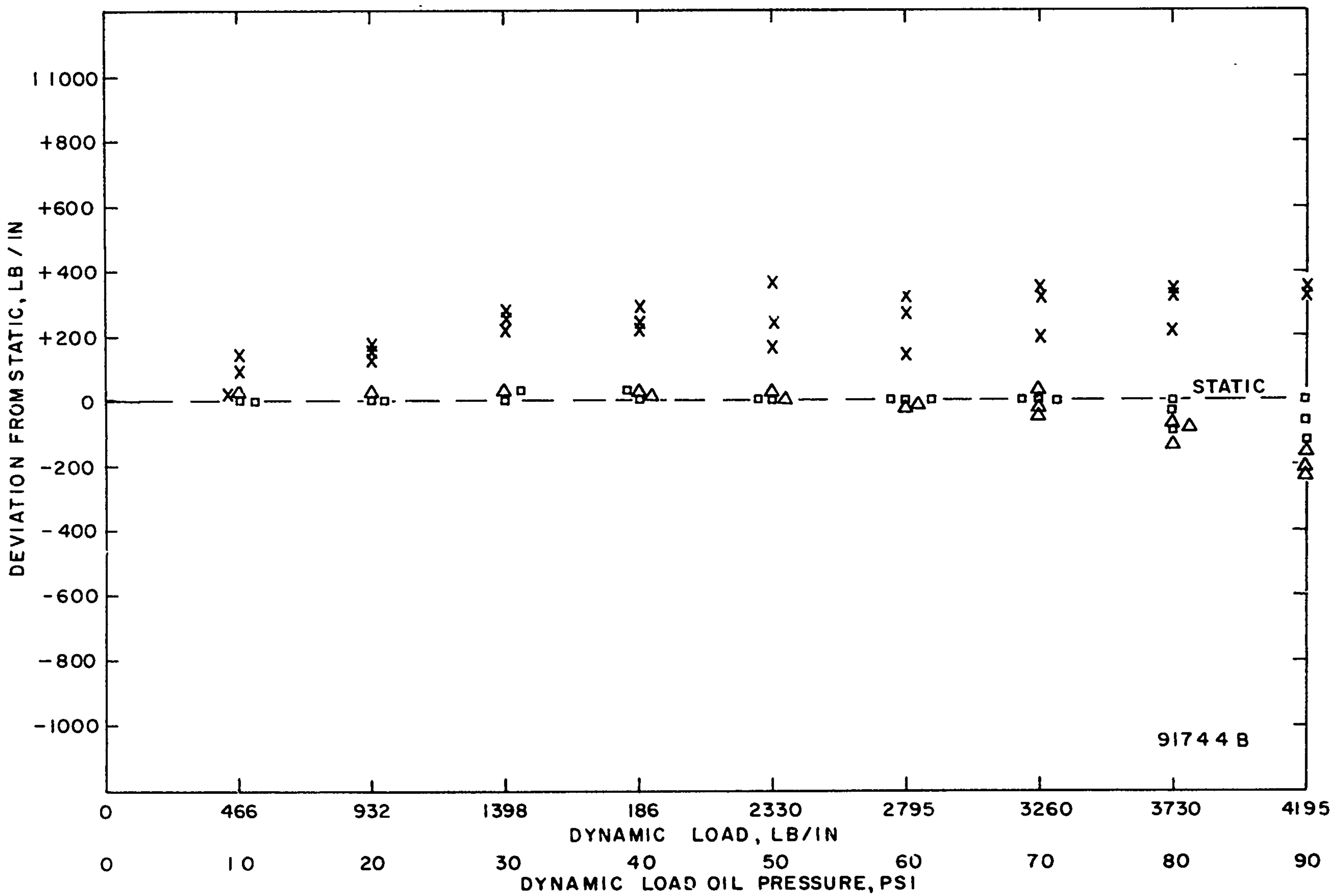


FIGURE 16. GEAR TOOTH LOAD DEVIATION BETWEEN STATIC AND DYNAMIC CALIBRATION WITH 0.005-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

induction heated gear temperatures). The results are shown in Figures 17, 18, 19, and 20. As can be seen in Figures 17 and 18, the 400°F calibration results compare very favorably with those obtained at 165°F conditions (Figs. 13 and 14). An inflection in the 500°F calibration results is noted in Figures 19 and 20 at load oil pressures of 20 and 25 psig. At this time, there is no explanation for this deviation; however, the data presented for the 500°F calibration represents only one set of results obtained to date and therefore are not considered final. It is felt that the deviation may be due to a temperature effect on the strain gage reading. Since the deviation is positive, the deviation cannot be due to any resistance to axial movement of the load shaft (due to a loss in clearance of the support roller bearings), loss of strain gage bond, strain gage cement creep, or change in the strain gage factor, for all these factors will always give a negative deviation. The only factors known which will give a positive deviation is a change in the strain gage environmental temperature or a resistance to turning of the driven or load shaft. A change in the strain gage temperature is not considered creditable, since great care is exercised to obtain thermal equilibrium at each of the load increments. Also, the resistance to turning of the load shaft would have to be due to rubbing of the shaft on the air and/or load seal. It is felt, however, if any rubbing of the shaft occurs, there would be as much or more resistance to axial movement of the shaft, thereby cancelling or over-riding the effect.

E. Discussion of High-Temperature Load-Carrying Capacity Results

1. Preliminary Results

The early high-temperature gear lubrication investigations, with induction heating of the test gears, were carried out at 400°F under Contract AF 33(616)-7223.(5) This work was done in order to compare the results obtained with the induction heating procedure with those obtained in the first high-temperature investigations, using the 400°F conventional heating procedure (400°F test oil and support oil temperature, test gears at temperature equilibrium of approximately 400°F). These data, shown in Table 3, were obtained using Nitralloy N steel test gears with standard backlash (0.002 - 0.006 in.) and standard diametral support bearing clearance (0.0005 in.). Since it has been subsequently shown that the load-carrying capacity values obtained with the standard backlash and standard support bearing clearance are doubtful, no emphasis is placed on the actual values shown.

The comparison of the results obtained by the two test methods is considered as the important point. It can be seen that the gear temperature in the conventional 400°F tests, measured at the load at which 22.5 percent

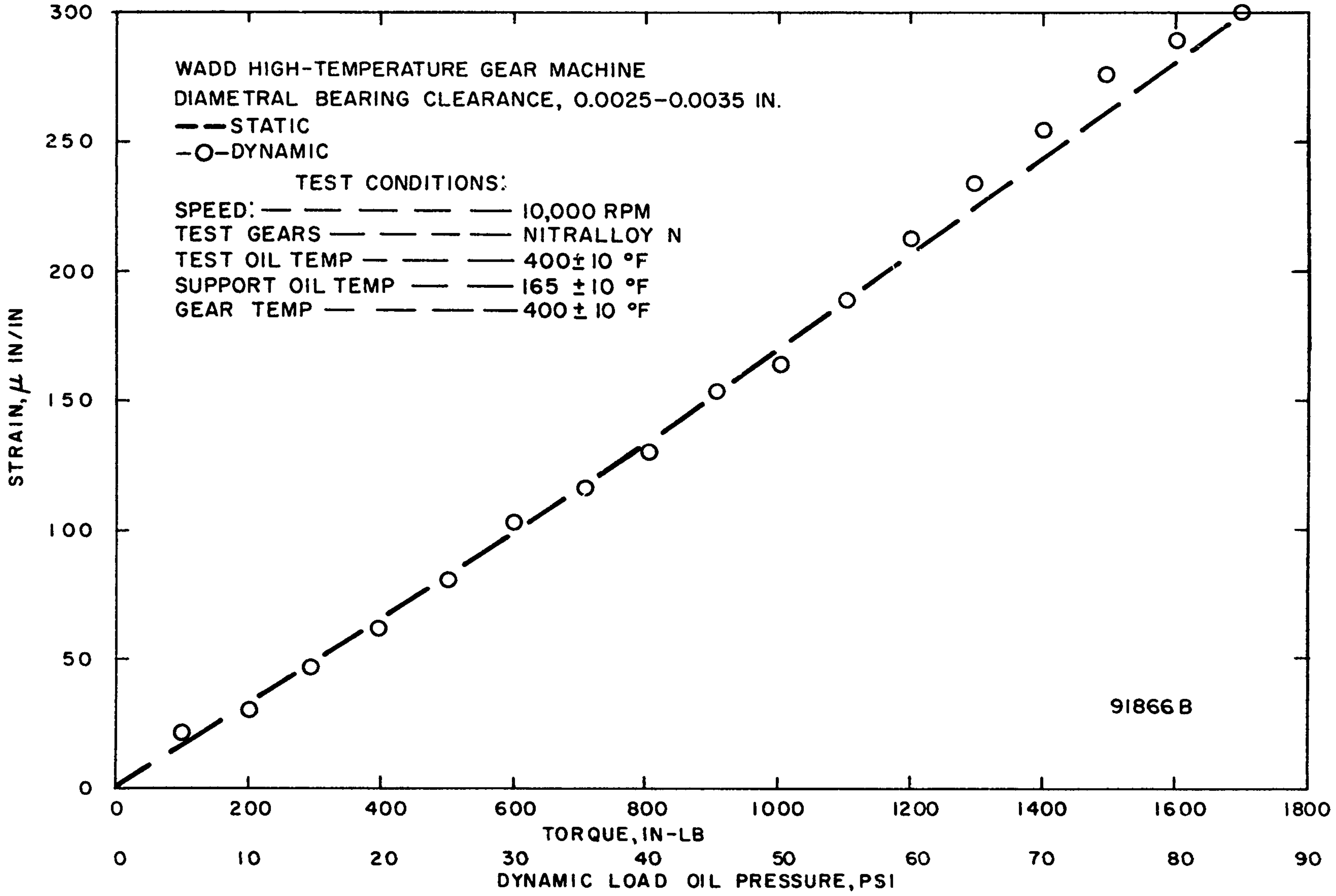


FIGURE 17. COMPARISON OF STATIC AND DYNAMIC CALIBRATION CURVES AT 400°F WITH 0.0025-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

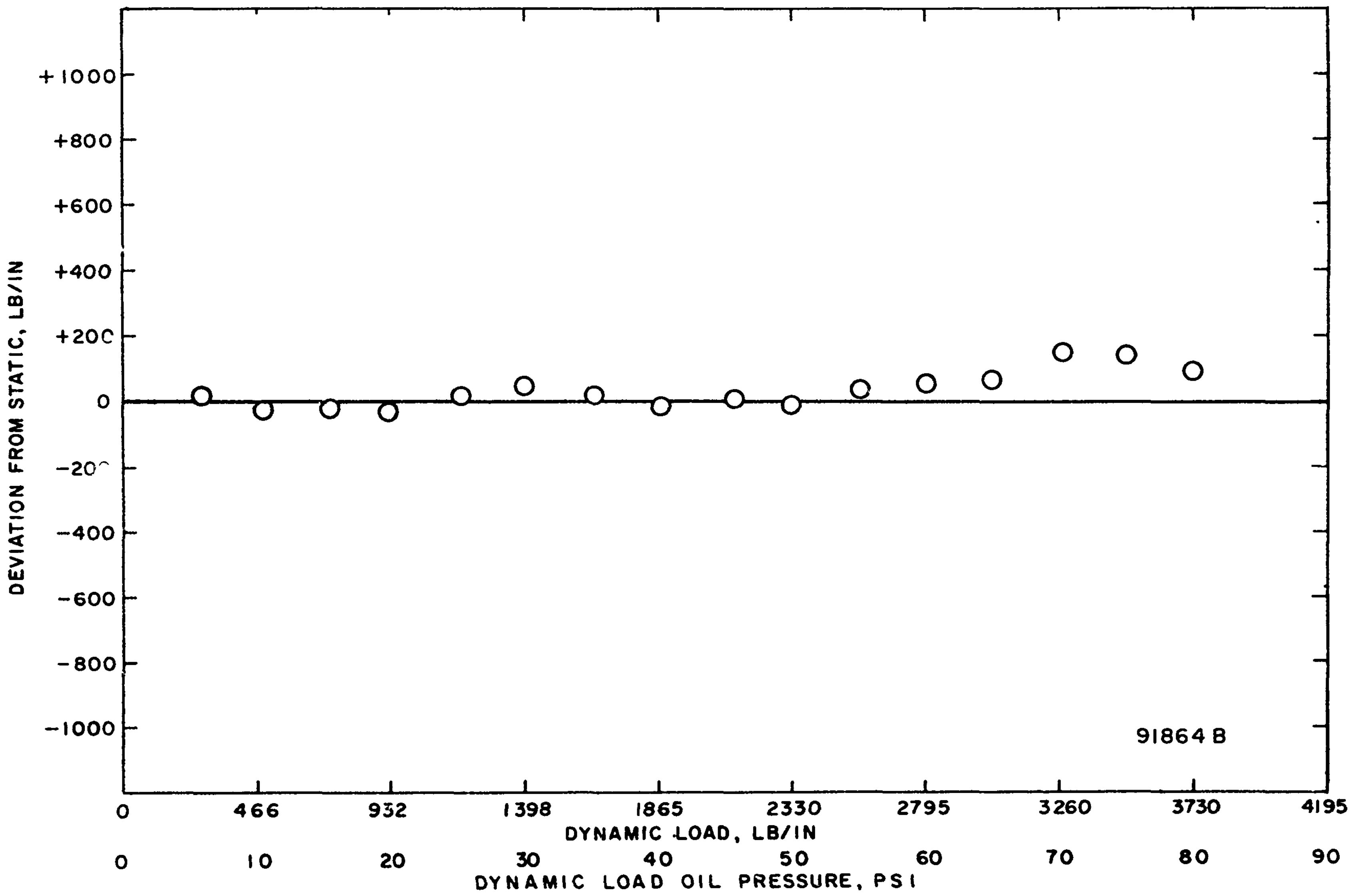


FIGURE 18. GEAR TOOTH LOAD DEVIATION BETWEEN STATIC AND DYNAMIC CALIBRATION AT 400°F WITH 0.0025-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

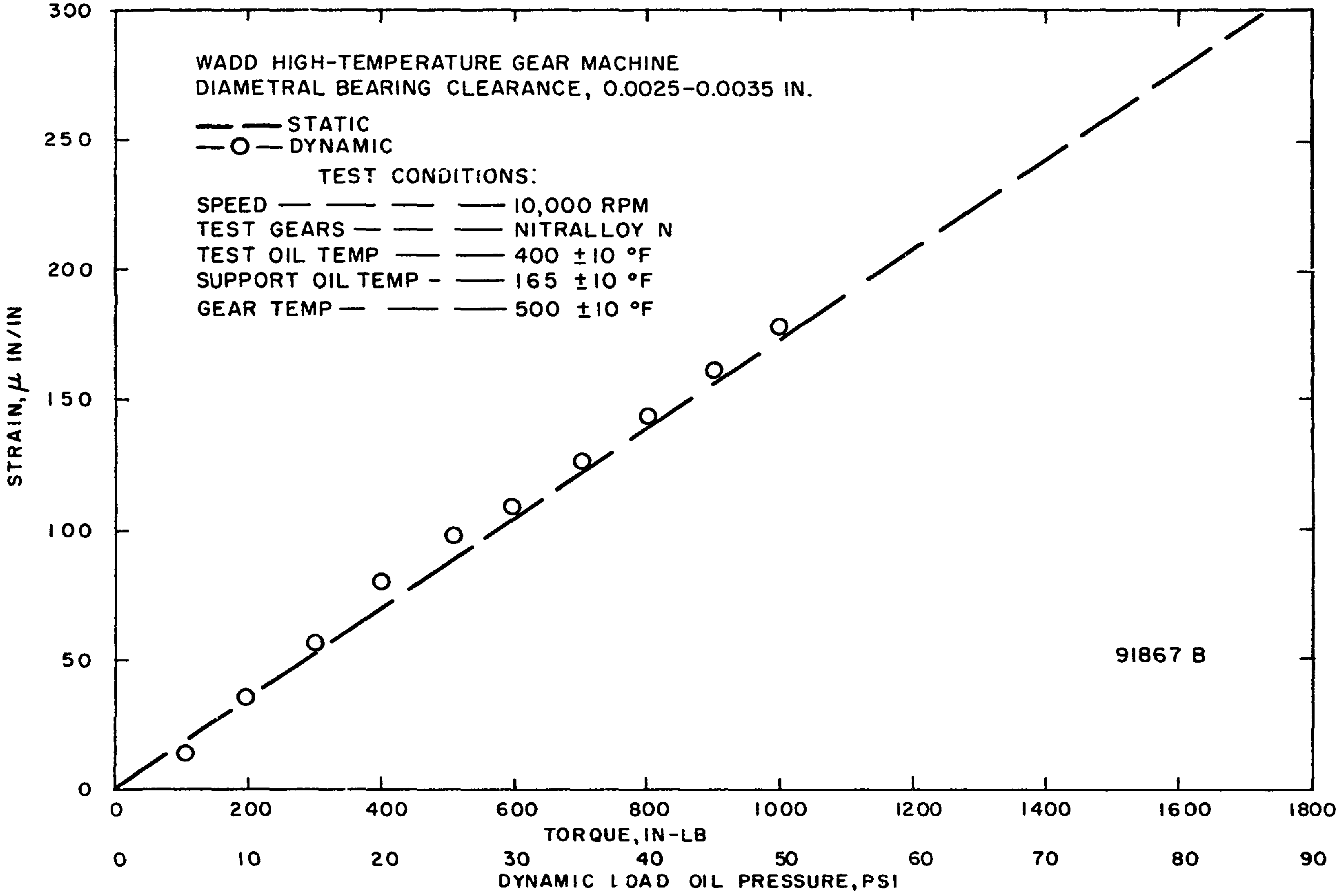


FIGURE 19. COMPARISON OF STATIC AND DYNAMIC CALIBRATION CURVES AT 500°F WITH 0.0025-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

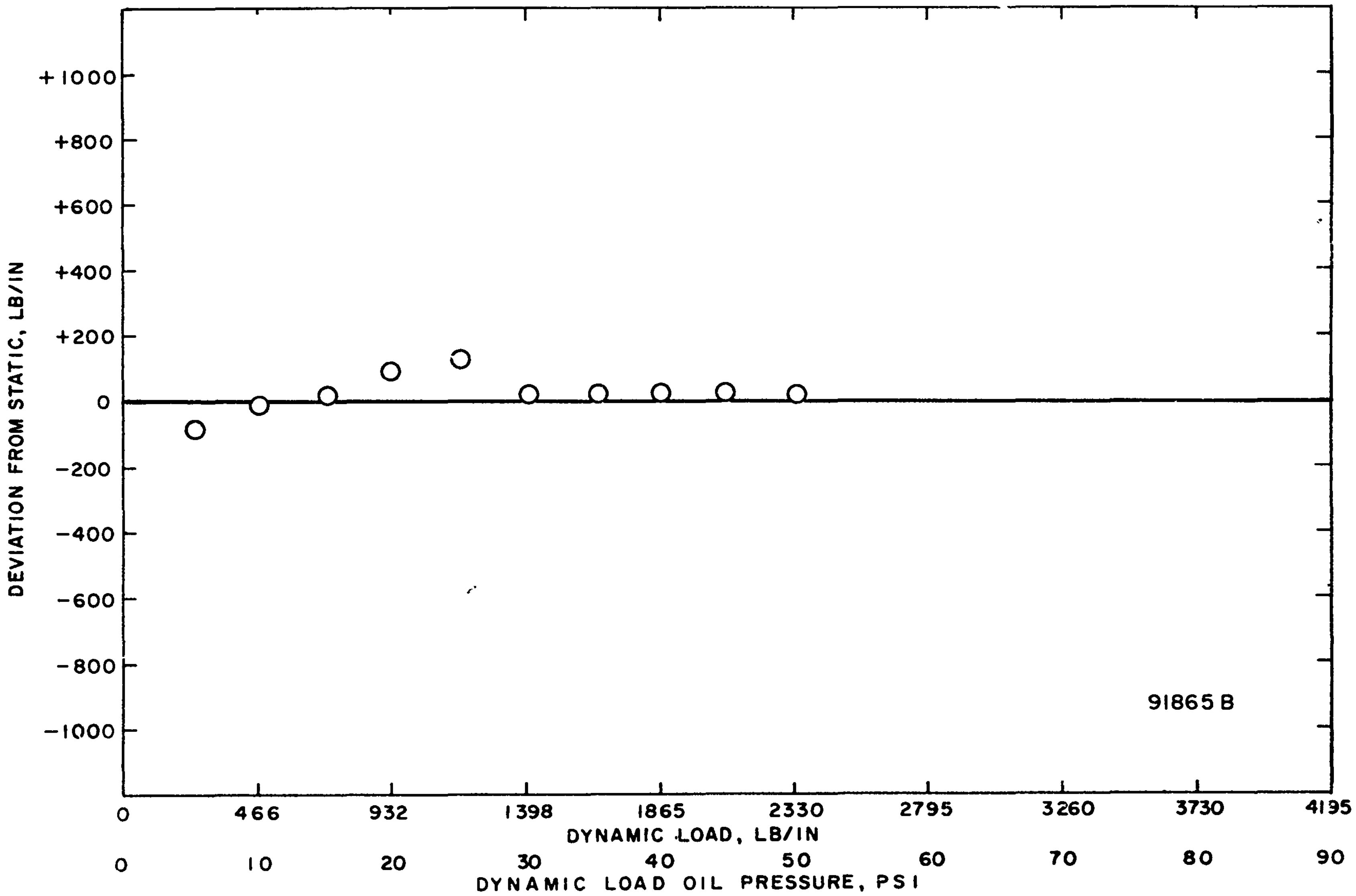


FIGURE 20. GEAR TOOTH LOAD DEVIATION BETWEEN STATIC AND DYNAMIC CALIBRATION AT 500°F WITH 0.0025-IN. DIAMETRAL SUPPORT BEARING CLEARANCE

TABLE 3. COMPARISON OF 400°F SCUFF-LIMITED LOAD RESULTS OBTAINED WITH THE INDUCTION HEATING METHOD AND THE STANDARD 400°F METHOD USING SwRI DESIGN NITRALLOY N TEST GEARS

	400°F Induction Heating Method(a)			Standard 400°F Method (b)		
Oil Code	Average Gear Temp. at 22.5% Scuff	Scuff-Limited Load, lb/in. A	Scuff-Limited Load, lb/in. B	Average Gear Temp. at 22.5% Scuff	Scuff-Limited Load, lb/in. A	Scuff-Limited Load, lb/in. B
GTO-313	400	2060	2540	480	2340	4310
	400	2620	2380	480	3080	2840
				480	1560	1520
				480	1270	1970
		2400			2360	
GTO-770	400	5990(c)	6230(c)	485	4580	4710
				485	3810	4220
				485	3940	4670
		6110			4320	
GTO-855	400	2910	2490	430	1240	1080
	400	3320	3220	430	790	1030
				430	1330	1430
				430	1360	1220
		2990			1190	
GTO-915, 0-60-23	400	1110	1620	420	1450	1150
	400	2100	1450	420	950	1090
				420	710	1670
				420	740	1150
		1570			1110	
GTO-939	400	1840	1570	400	1340	1670
	400	1470	1600	400	1540	1220
		1620			1440	
LRO-11	400	1830	1710	420	1280	1310
	400	1400	1640	420	1520	1400
				420	840	1500
				420	1250	1510
		1640			1330	
LRO-13	400	1780	1990	-	1620	1720
	400	2160	2460	-	1430	1640
				-	1760	1880
				-	1710	1410
		2100			1650	

(a) Tests were made using WADD high-temperature gear machine No. 2.
(b) Tests were made using WADD high-temperature gear machine No. 1.
(c) Values obtained by extrapolation. Test was terminated at 5600 lb/in. tooth load.

scuff was obtained, are always somewhat above 400°F. With the induction heating method, the gear temperature is controlled at 400°F. Therefore, the increased load-carrying capacity for the lubricants tested, using induction heating at a controlled gear temperature of 400°F, was attributed to this difference in gear temperature since it has been demonstrated that with an increase in test gear temperature, the load-carrying capacity of most lubricants tends to decrease. From these data, it was concluded that the induction heating method of heating the test gears produced no adverse effects in load-carrying capacity determinations and could be used with confidence in high-temperature test mehod development.

In an effort to determine the effectiveness of induction heating and operation of the WADD ' igh-temperature gear machine at test gear temperatures above 400°F, load-carrying capacity determinations were obtained on several lubricants using Nitralloy N steel test gears at controlled gear-web temperatures, varied in 50 or 100°F increments, from 400 to 700°F. The test lubricant supply temperature was maintained at 400°F, and the support oil supply temperature was maintained at 165°F. The test lubricants were selected on the basis of their 400°F load-carrying capacity ratings such that high, medium, and low load-carrying capacity lubricants were included in the study. No great amount of difficulty was encountered in the gear machine operation or temperature control of the induction-heated gears during the tests. The first difficulty encountered was excessive smoke in the gear case, at gear-web temperatures of 500°F and above, which interfered with the infrared radiation measurements. This was overcome by installing a phenolic tube in the gear cover with the free end in close proximity to the area of the narrow test gear at which radiation measurements are made. With a small exhaust blower attached to the gear case, a slight draft of air was drawn through the tube, thereby clearing the area of smoke and the small amount of oil mist normally present.

During testing at gear-web temperatures of 500°F and higher, it was noted that the gear machine speed would drop somewhat while the gears were being heated to the desired test temperature. This drop in machine speed was believed to be due to thermal expansion of the test gears, thereby decreasing the test gear clearance and backlash, with interference loading of the test gears being the final result. A rough check on the gear machine starting drive torque was made by use of a torque wrench on the end of the driven shaft while the test gears were induction-heated over a temperature range of 400 to 600°F. A plot of these rough data is shown in Figure 21. A noticeable increase in torque was obtained at gear-web temperatures between 550 and 600°F. It was clear that means must be sought to eliminate the gear tooth interference, in order to permit gear lubrication studies to be made at high temperatures.

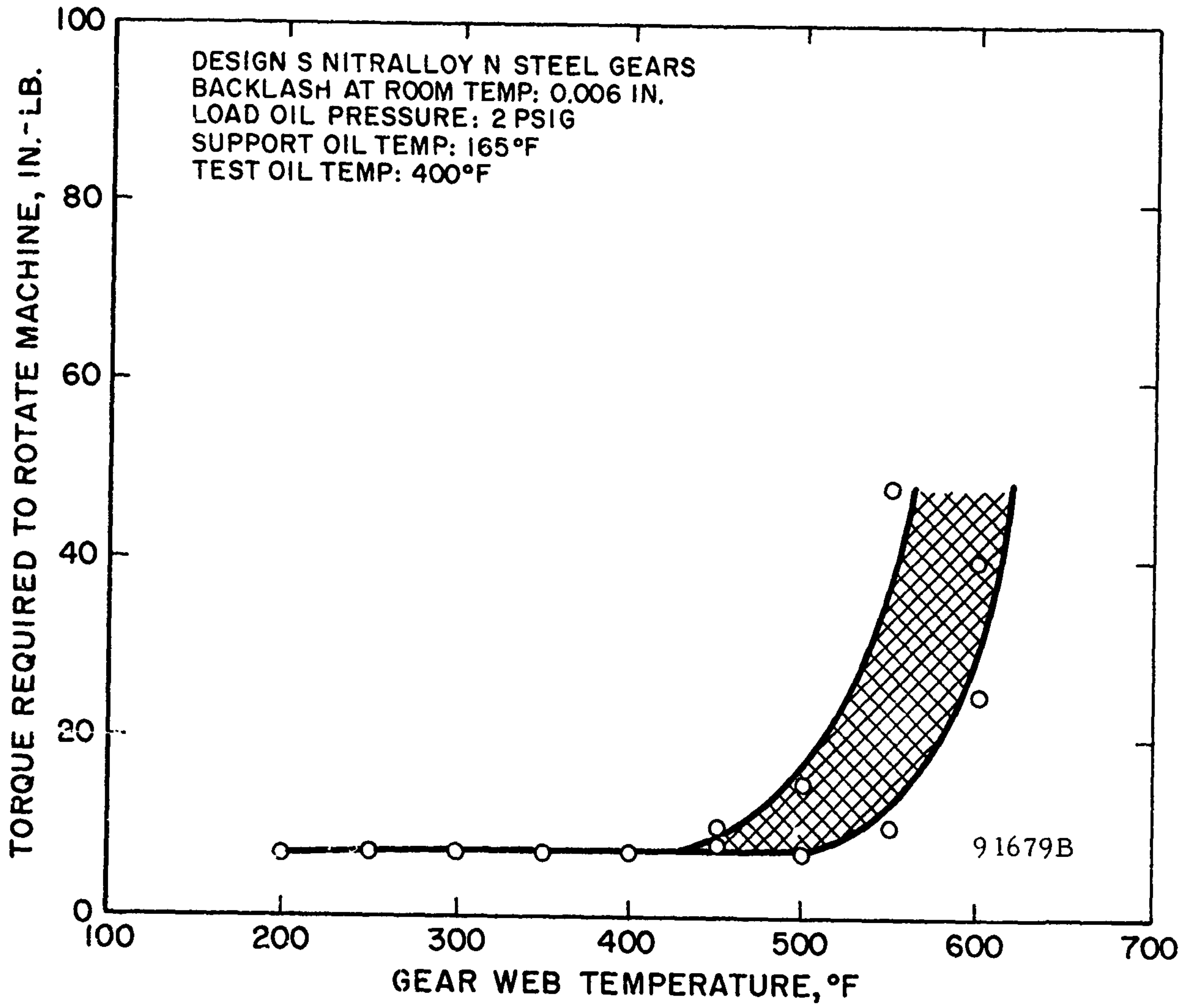


FIGURE 21. VARIATION OF STARTING DRIVE TORQUE WITH GEAR-WEB TEMPERATURE

The simplest way to do so, without otherwise changing the design characteristics of the test gears, appeared to be an increase in the gear backlash. **Further**, it was decided that the geometry of the narrow test gears (those used for rating purposes) should not be changed, and that any additional backlash required should be obtained by modifying the wide test gears.

Measurements showed that the nominal backlash of the standard Nitralloy N steel test gears was 0.005 in.; and, with this backlash, it was found that tooth interference was likely to occur at a gear-web temperature of 450 to 500°F. From calculations based on the coefficient of expansion of Nitralloy N steel, it was found that the nominal backlash required to avoid interference was approximately 0.008 in. at 700°F and 0.010 in. at 800°F. In order to check these calculations, used wide gears with very low amounts of scuff on the gear teeth were reground to give lacklashes of 0.008 - 0.010 in. and 0.011 - 0.014 in., respectively. These reground wide gears, as well as wide gears with standard backlash (0.005 in.), were then installed in a WADD high-temperature gear machine, along with the standard narrow gears. The gears were heated by induction heating and the gear-web temperature measured and controlled by an infrared radiometer in conjunction with an on-off controller-recorder. First, experiments were made by manually rotating the gears and noting the temperatures at which a slight resistance to smooth rotation was experienced. The data so obtained are shown in Figure 22. The gears were then run at 10,000 rpm with lubrication and at no load, at the temperatures so determined. There was no indication of tooth interference during these runs; and, upon inspection after the runs, no evidence of scuff due to tooth interference was found.

Based on the results of these experiments, a supply of Nitralloy N steel test gears with a backlash of 0.011 to 0 014 in. was ordered. As stated before, standard geometry for the narrow test gear was retained, and the increased backlash was obtained by modifying the wide test gear.

Reference was made earlier of the need for larger diametral clearances in the support roller bearings. As reported, the support roller bearing diametral clearance of 0.0025 in. was obtained by grinding the inner surface of the outer race of standard bearings. Load-carrying capacity tests were then made at 165 and 400°F on three lubricants to determine the effect that the larger bearing clearance would have on the established load-carrying capacity of these lubricants. The results obtained are shown in comparison in Table 4 with those obtained previously with standard diametral clearance (0.0005 in.) bearings. As can be seen, a lower rating level was obtained with the increased support bearing clearance. In the 400°F tests, the rating level is considerably lower than was

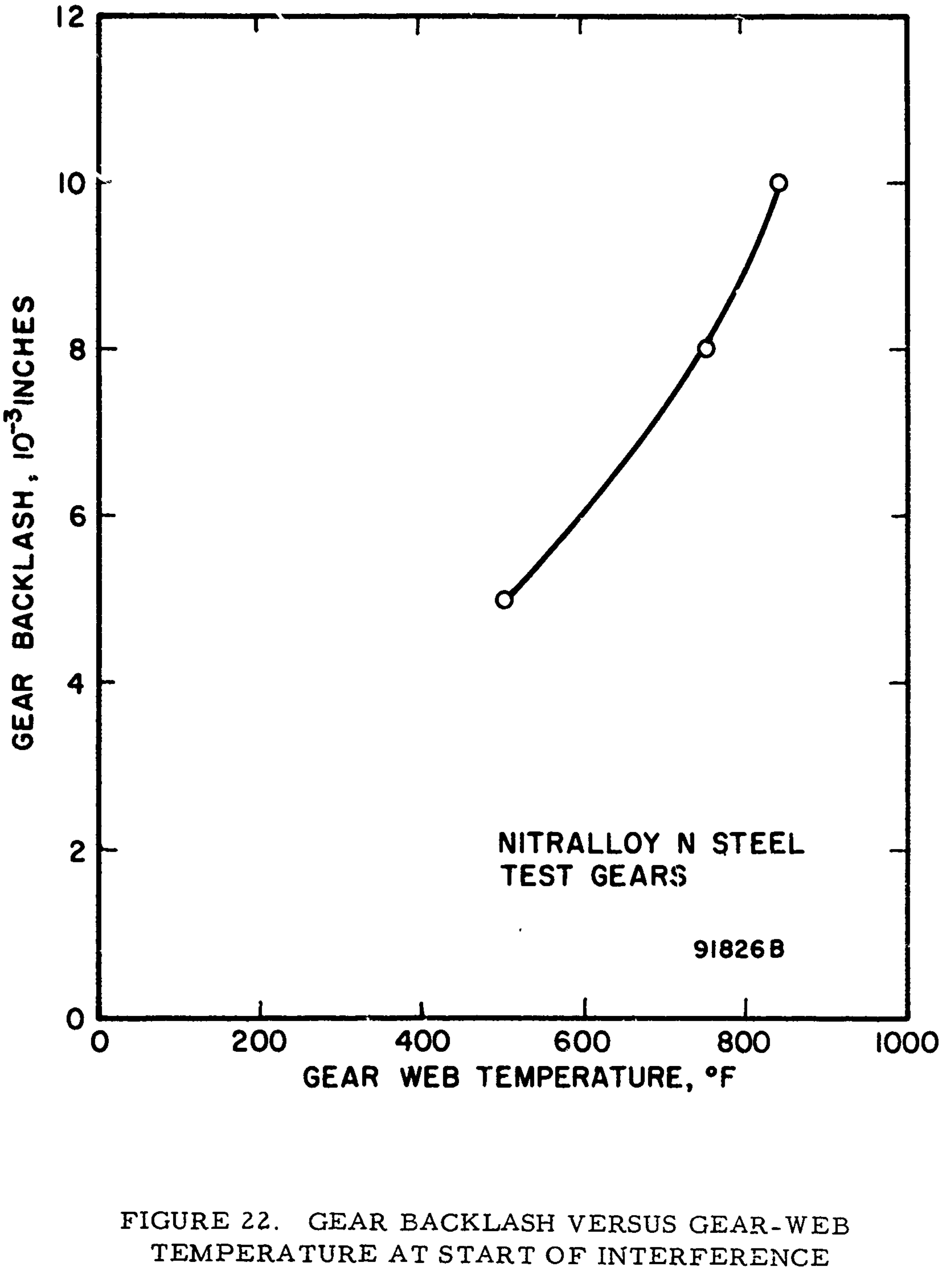


FIGURE 22. GEAR BACKLASH VERSUS GEAR-WEB TEMPERATURE AT START OF INTERFERENCE

TABLE 4. COMPARISON OF 165°F AND 400°F TEST RESULTS OBTAINED WITH 0.0005 AND 0.0025 IN. SUPPORT BEARING CLEARANCES

	Scuff Limited Load, lb/in.							
	Bearing Clearance 0.0005 in.				Bearing Clearance 0.0025 in.			
Oil	165°F		400°F		165°F		400°F	
Code	A	B	A	B	A	B	A	B
GTO 770	5740	5720	4580	4710	5190	4930	3200	3880
			3810	4220	5320	4750	4090	3620
			3940	4670				
	5730		4320		5050		3700	
O-60-26	2400	2280	1340	1670	1920	(a)	550	570
	2320	2340	1540	1220	1540	2060	520	610
	2340		1440		1800		560	
MLO-61-1011	2000	2480	1450	1150	1640	2170	450	560
	1870	2010	950	1090	2040	1720	600	350
	1790	1740	710	1670				
			740	1150				
	1980		1110		1890		490	

Two-gallon high-temperature test oil system and standard backlash test gears used. Conventional heating used for all tests.

(a) "B" side of test lost due to mechanical failure in the gear machine.

anticipated and indicated that the standard support bearings had more of an effect on load-carrying capacity than was suspected prior to the calibration studies.

2. 425 and 500°F Load-Carrying Capacity Results

In order to provide a basis of comparison for the higher temperature investigations, it was decided to investigate the load-carrying capacity results obtainable with the increased backlash gears at a lower temperature, 425°F. Load-carrying capacity determinations were made on five lubricants. A minimum of four determinations were made on each of the lubricants at 425°F test gear temperature. On the basis of the satisfactory results obtained at 425°F, the lubricants were then run at 500°F test gear temperature. The results of the 425 and 500°F load-carrying capacity determinations are shown in Table 5.

The average load-carrying capacity values obtained in the 425°F tests were in line with previous experience and considered valid. However, the repeatability obtained on MLO-61-1011, with a standard deviation/mean of 46.3 percent, was of concern. After the first large spread between the "A" and "B" determinations were obtained on MLO-61-1011, the test conditions and test procedure were carefully observed in the succeeding tests on the lubricant. However, no discrepancies were found, and, since the scuff pattern appeared to be normal, and dimensional and metallurgical examinations of the gears showed the test gears to be not causative in the deviation, the induction heating method was suspected. Load-carrying capacity determinations were then made on the lubricant with another WADD high-temperature gear machine at 400°F conventional test conditions. In addition to this, the two-gallon test oil system was used. The repeatability, however, was only slightly improved in that a deviation of 31.4 percent was obtained.

Satisfied that the repeatability difficulties were due to either the instability of the lubricant or some other unknown and indeterminable cause, the program was continued. The repeatability obtained on the remaining lubricants ranged from about 10 to 13 percent, considerably better than that obtained with the MLO-61-1011.

Load-carrying capacity determinations were next made at 500°F test gear temperature. Here, once again, the repeatability for MLO-61-1011 was poor, with the other lubricants remaining at about the same level (10 - 13 percent) as that obtained at 425°F.

In comparing the load-carrying capacity obtained on these lubricants at the two test gear temperatures, it can be seen that the 500°F

TABLE 5. RESULTS OF HIGH-TEMPERATURE LOAD-CARRYING CAPACITY DETERMINATIONS

	Load-Carrying Capacity, lb/in.			
	425°F		500°F	
Oil Code	A	B	A	B
Ref. Oil "B"	4740	5030	5550$^{(a)}$	(b)
	4930	3700	5470$^{(a)}$	5660$^{(a)}$
	4600		5560	
GTO-770	3690	3730	4390	4090
	4080	4320	3990	4370
	3960		4210	
O-60-26	1080	740	1530	820
	1010	940	1010	980
	940		1090	
O-61-20	1040	1060	1220	1530
	1260	820	1360	1170
	1050		1320	
MLO-61-1011	1000	530	470	1700
	1690	220	570	1930
	800	1090		
	680	1140		
	680	1590		
	940		1170	

Half-liter test oil system and increased backlash test gears used.

(a) Extrapolated value.

(b) "B" side not run due to tooth breakage during "A" side run.

load-carrying capacity is increased over that obtained at 425°F. In view of all previous experience where an increase in test gear temperature has produced a decrease in load-carrying capacity, the increase in load-carrying capacity indicated for all of the lubricants was unexpected. The 500°F gear temperature tests results reported have just recently been completed, and time has not been sufficient to allow investigations to be made on the possible reasons for the indicated increase in load-carrying capacity. The data are currently being analyzed from the standpoint of the increases in viscosity and neutralization number obtained during each determination. Cursory examination of these data has not indicated any definite trends.

F. Conclusions

Preliminary calibration studies have shown the 0.0025-in. diametral clearance of the support roller bearings to be satisfactory for 500°F induction heated test gear operation in the WADD high-temperature gear machine.

Although there is some question with respect to the results obtained in the 500°F load-carrying capacity determinations reported, it is concluded that the performance of the WADD high-temperature gear machine and its supporting equipment is satisfactory for this temperature level.

G. Future Program

Further calibration studies will be made at 500°F test gear temperature during the next reporting period. Also, calibration studies have been planned up to 700°F to determine the highest permissible gear temperature for the 0.0025-in. diametral clearance in the support roller bearings. These studies will be made in 50°F increments between 500 and 700°F until there is an indication of the occurrence of bearing clearance loss.

The results obtained at 500°F test gear temperature will be analyzed in an effort to determine the reason or reasons for the indicated increase in load-carrying capacity reported.

Additional investigations into gear load-carrying capacity test method development at 500°F test gear temperature will be made if the aforementioned 500°F data analysis indicates such necessity.

High-temperature gear tests will be conducted on lubricant candidates submitted by ASD as they become available.

III. THREE-BALL/CONE FATIGUE TESTER

A. General Remarks

The 3-ball/cone fatigue tester is a part of a broad program to study the effects of lubricants on ball bearing fatigue and lubricant performance under extreme operating conditions of temperature, load, and speed.

Current emphasis has been on a study of bench-type bearing fatigue testers, and on the physical design of a 3-ball/cone tester.(7) The study has been coordinated with a parallel study made by the Bearing Fatigue Panel of the CRC Aviation Group on Gas Turbine Lubrication.

B. Study of Bench-Type Fatigue Testers

1. SwRI Study

In 1960, SwRI was requested by ASD to make a brief survey of the state of the art of bench-type fatigue tests. It was recognized that the important advantages of bench-type fatigue tests were the simplicity and low cost of the test apparatus and the low cost of conducting the tests. However, the correlation between the bench-type tests with full-scale bearing tests needed to be resolved. In particular, a large number of bench-type testers were known to be available, and it was necessary to select a design that would best answer the requirements for evaluating lubricants for advanced gas turbine engine bearings. The requirements considered important were geometric simplicity, provisions for varying stress level and stress frequency, provision for varying spin-to-roll ratio, high-temperature capability to 800°F or higher, recirculating lubrication system with provision for operating in an inert gas atmosphere, provisions for measurement of speed, load, friction torque, and provision for reliable indication of fatigue failure.

A number of bench-type fatigue testers employing simple test specimens (usually balls) were examined

Barnes one-ball tester(8)
GE one-ball tester(9)
NACA (two-ball) spin tester(10)
SKF three-ball/flat-washer tester(11)
Barwell four-ball tester(12)
Modified Barwell (3-ball/cone) tester(7)
NASA five-ball tester(13)

With some of these testers, considerable lubricant evaluation data were available; with others, practically no such information appeared to have been published. In some cases, correlation between the bench tests and full-scale bearing tests was claimed but not substantiated with organized data. However, in most instances, there were no valid reasons to suspect that reasonable correlation could not be obtained.

It appeared that many of the testers were available in several versions with presumably different performance capabilities. However, no single design was known to possess features that would satisfy all of the requirements set forth previously. Accordingly, it was concluded that all of the specified requirements could be met only by the design and construction of a special tester, based upon the principle of one of the basic designs listed above.

After careful consideration of all factors, it was felt the selection of a basic design would be among the following:

SKF three-ball/flat-washer tester
Barwell four-ball tester
Modified Barwell (3-ball/cone) tester
NASA five-ball tester

All of these basic designs appeared to be capable of being developed for high-temperature operation and to be simple and low in initial cost and low in cost of operation. Among these, the modified Barwell (3-ball/cone) tester was considered to be the most promising, due to its flexibility in varying the spin-to-roll ratio.

2. CRC Study

Almost parallel to the SwRI study has been a similar study conducted by the Bearing Fatigue Panel of the CRC Aviation Group on Gas Turbine Lubrication. This panel took into consideration a number of requirements similar to those given previously but examined a larger number of bench-type testers. These were then narrowed down to the same basic types examined in the SwRI study, from which three were selected as being most promising; the modified Barwell tester, the NASA five-ball tester, and the Barnes one-ball tester. However, no final choice has been made at this writing between these two basic types.

C. Design of 3-Ball/Cone Fatigue Tester

1. Design Requirements

On the basis of the comments and recommendations of the two aforementioned studies, ASD directed SwRI to design for their consideration a bench-type fatigue tester using the principle of the modified Barwell tester (3-ball/cone tester).

The design criterion for the proposed tester was outlined by ASD to include the following general requirements:

(1) Test specimen:

  (a) Material - High-temperature bearing-quality steel
  (b) Simple geometry

(2) Initial contact stress level:

  (a) Variable up to 700,000 psi maximum

(3) Temperature:

  (a) Specimen - 1000°F maximum, 700 to 800°F acceptable; 150 to 250°F minimum

  (b) Lubricant - 750°F maximum, 100°F minimum

(4) Kinematics of test elements:

  (a) Variable stress frequency (maximum cone speed to be 10,000 rpm)

  (b) Variable spin-to-roll ratio

(5) Lubrication:

  (a) Recirculating system

  (b) Atmosphere control using inert gases at atmospheric pressure.

(6) Instrumentation and measurement capability:

  (a) Failure detector to shut down the facility

  (b) Timer or spindle revolution counter

  (c) Spindle speed indicator

  (d) Specimen and lubricant temperature control

(e) Load control

(f) Lubricant flow rate measurement

(g) Torque measurement (optional)

(h) Conductivity or film thickness measurement (optional)

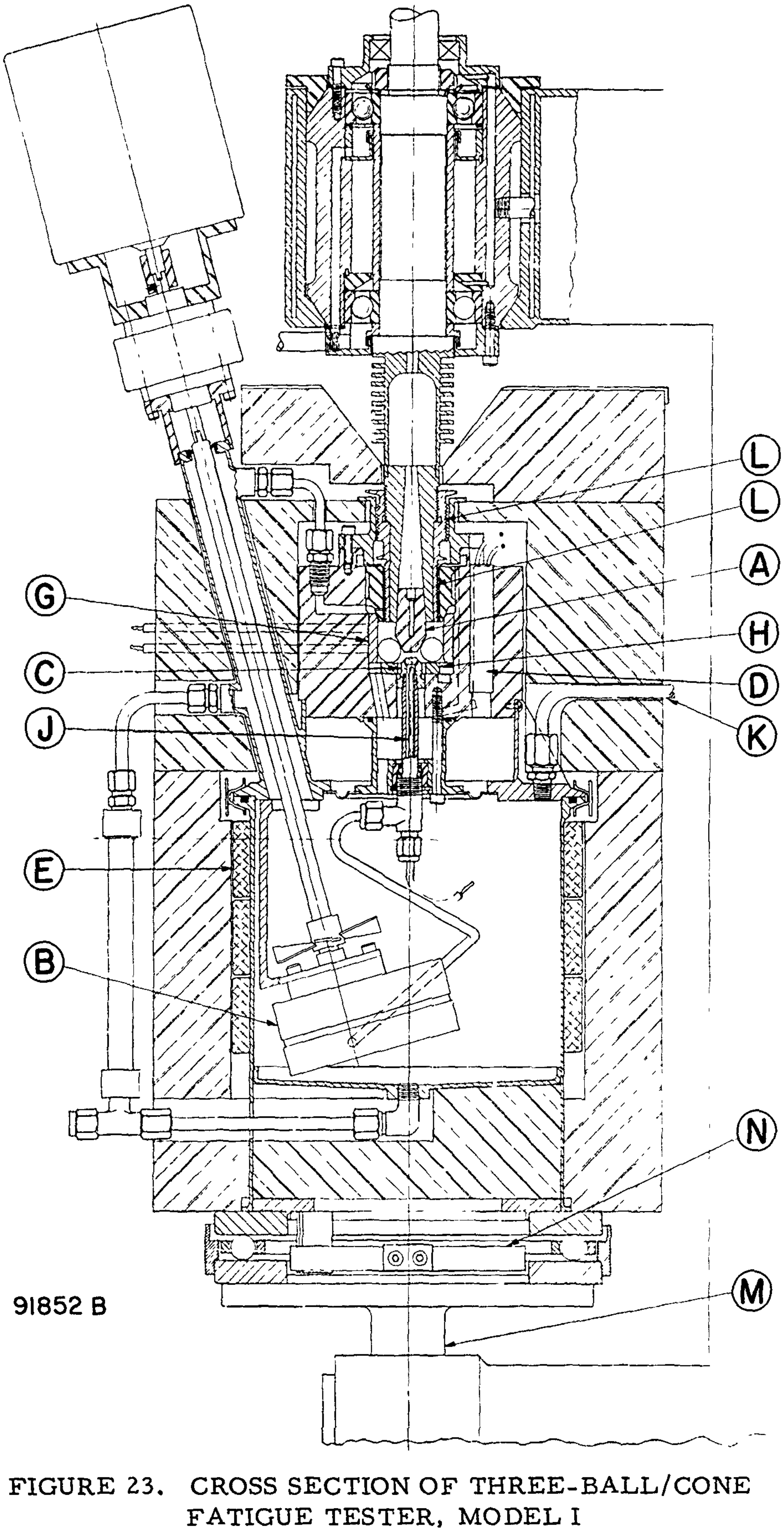
The ultimate purpose of the 3-ball/cone fatigue tester would be to provide a reasonably simple device capable of evaluating the bearing fatigue characteristics of lubricants over a wide range of conditions.

2. Three-Ball/Cone Fatigue Tester, Model I

General Design. The initial design version of the 3-ball/cone fatigue tester, designated "Model I," is shown in Figure 23. The frame, drive, and load application details are not illustrated in the drawing. These will be described later.

In general, the conical specimen, A, rotates against three balls, equally spaced by a retainer. The lubricant is circulated by the submerged gear pump, B, located in the integral sump, and is directed against the ball-cone interface by the replaceable nozzle, C. Lubricant return is by gravity through drain holes. Loading is accomplished by dead weights and a lever arrangement below the sump. The drive for the spindle consists of a 3600 rpm D.C. motor with pulleys and timing belt to give a continuously variable spindle speed up to 10,000 rpm. Heat is supplied to the test region by cartridge heaters, D, and to the sump by band heaters, E. The entire apparatus is insulated to reduce heat loss to the atmosphere.

Test Specimen and Test Region. The conical test specimen, A, driven by the spindle through a self-actuating taper, is positioned in a cluster of three equally spaced 1/2 in. diameter balls. The balls are equally spaced about the cone specimen by a retainer. The balls are confined in a chamber made up of a ring, G, and a washer, H. The ring and cone temperatures are measured by thermocouples. The signal from the latter thermocouple is removed from the rotating shaft through slip rings.(14) Heat is supplied to the test region by six cartridge heaters inserted into snug-fitting holes in the block. Preliminary tests made using these heaters in a block similar to that proposed in the design indicate that a temperature of 1000°F can be reached within 1-1/2 hours.


L
L
A
G
H
C
D
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E
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M
91852 B

FIGURE 23. CROSS SECTION OF THREE-BALL/CONE FATIGUE TESTER, MODEL I

The cone angle of the specimen may be varied from 60° to 90°, corresponding to contact angles of 30° and 45°, respectively. The spin-to-roll ratio of the cone against the ball and the number of stress cycles on the cone per revolution may be varied by varying this cone angle. With a 30° contact angle cone, each revolution of the spindle will result in 2.2 stress cycles on the cone, and a spin-to-roll ratio of 0.26. A 45° contact angle results in 2.0 stress cycles per cone revolution, and a spin-to-roll ratio of 0.53.

Lubricant Supply System. The test lubricant system is a closed, positive-pressure, recirculating system capable of being blanketed with an inert gas. The lubricant sump is an integral part of the test region. The consequent elimination of long lines connecting a remote sump from the test region reduces the temperature differential between the bulk oil and that entering the test chamber to a minimum. It also makes it possible to measure torque by eliminating the stiffness due to external lubricant lines between the sump and the test head. A small electric motor drives the test oil pump through a reduction gearbox. The pump is a positive displacement gear pump running submerged in the lubricant. This manner of pump operation reduces thermal distortion of the parts due to temperature variation throughout the pump.

The sump is heated by three band heaters with provision for a plate heater underneath the sump if necessary. Previous experience with similar sumps and heaters indicates no difficulty in reaching 750°F test lubricant temperature.

The sump is well insulated and is thermally isolated from the test region by a dead air space. Such isolation makes it possible to independently regulate the temperature of the sump and test region. The sump temperature is measured and controlled through thermocouples immersed in the lubricant. A thermocouple, J, extends to the tip of the nozzle to measure the temperature of the lubricant entering the test region.

To reduce lubricant oxidation and to simulate conditions in a gas-blanketed lubricant system, the lubrication system of the tester has been designed to operate under a small positive gage pressure using a nitrogen gas blanket. Escape of lubricant-entrained gas past the spindle is prevented by rotating screw seals, L. Gas pressure build-up is prevented by venting through a reflux condenser attached at K. The condenser may be arranged to either reflux back into the sump, or to an external waste can. In the latter case, make-up lubricant must be added periodically.

Load System. The axial load on the spindle will vary from about 300 to 500 lb for contact angles of 30° and 45°, respectively, giving an initial maximum Hertz contact stress of 700, 000 psi. The load is applied from the bottom of the rig. Dead weights applied to a 10 to 1 lever system push the platform, M, upward thereby transmitting the axial load through the ball thrust-bearing and thence to the sump walls and the test block. The platform is guided by a linear ball bearing to eliminate any tendency toward tilting.

Torque Measurement. Friction between the rotating cone specimen and the balls produces a torque on the test block and sump assembly. This assembly is restrained by two flexible metal arms, N. Strain gages bonded to these arms measure the deflection resulting from the torque. The ball thrust-bearing torque tends to counteract the friction torque so that the torque measured by the flexible arms is actually less than the friction torque. If the thrust-bearing torque is too large so that it tends to mask the friction torque, it is planned to substitute a hydrostatic air bearing in its place.

Drive System. The details of the drive system are not completed pending final decision on the remainder of the tester design. It is planned that a 1/2-hp, 3600-rpm D. C. motor be used to provide a continuously variable speed. The motor will drive the spindle through pulleys and a timing belt with a maximum spindle speed of 10, 000 rpm. Spindle bearings will be special preloaded, high-speed, angular-contact bearings using mist lubrication.

In order to gain access to the test region for purposes of replacing test specimens, the spindle assembly will be removable, much in the manner that a lathe collet may be removed. Tapered surfaces will assure alignment.

Frame. The final frame design is also not complete pending final decision on the remainder of the tester design. It is anticipated that it will be a "C" frame of welded steel box construction. Extra bracing will be provided at points of attachment.

Test Termination Control. When a specimen fatigues, with a resulting fracture of the surface, the irregularity will produce a vibration in the spindle assembly. This vibration will be picked up by a microphone transducer mounted on the frame. The transducer signal resulting from the vibration at failure will be used to shut-off all electrical inputs, the inert gas supply, and stop all recording instrumentation. The final design of this phase of the rig will be made after the construction and initial operation of the tester.

3. Three-Ball/Cone Fatigue Tester, Model II

A second version of the tester is presently under consideration. This version, Model II, will incorporate features designed to eliminate some characteristics of the Model I that have been thought to be objectionable.

The principal features of Model II will be the application of load down through the spindle instead of up through the sump support, and the elevation of the thrust-bearing from below the sump to a plane nearer the plane of the ball specimens. This bearing will be an annular type hydrostatic air bearing. It is believed that these changes will provide greater stability of the sump and test block region and improve alignment in the test region.

D. Future Work

Immediate effort will be devoted to the design of the Model II tester. Following its completion, it is planned to discuss the design of both models with ASD and CRC. An early date is anticipated for the initiation of the construction of one of the models, based on a comparison of the two versions.

IV. LUBRICANT OXIDATION-CORROSION

A. General Remarks

The objectives of the lubricant oxidation-corrosion phase are to develop evaluation apparatus and procedures for determining the performance of high-temperature gas turbine lubricants and to evaluate the oxidation-corrosion characteristics of candidate lubricants under environmental conditions representative of those encountered with Mach 3 class gas turbine engines.

During the period covered by this report, work has been concentrated on a reproducibility program on a finalized 425°F oxidation-corrosion test procedure, and the construction of and preliminary tests on a high-temperature apparatus to evaluate the oxidation-corrosion properties of lubricants intended for use at 500°F and higher. In all work on this phase of the project, liaison has been maintained with the Bench Tests Panel of the CRC Aviation Group on Gas Turbine Lubrication.

B. 425°F Oxidation-Corrosion Test

1. Apparatus and Procedures

An 18-hour 425°F oxidation-corrosion test, developed under Contract AF 33(616)-7223,(5) has been used in this phase of the program. Using engine test lubricant performance data provided by ASD, a test was developed which yielded satisfactory correlation with engine test results. These studies started from a test procedure and apparatus developed by Celanese Chemical Company. During further development of the test, at SwRI, to obtain a satisfactory correlation of the 425°F oxidation-corrosion data with ASD engine data, it was necessary to modify test conditions and procedures rather drastically, so that the test in its present form resembles the original only in apparatus and operating temperature.

The equipment and test procedures which were developed for evaluating the oxidation and corrosion tendencies of lubricants at 425°F are given in detail in the Appendix for reference. This test procedure is still in draft form, but no significant changes are anticipated.

2. Test Reproducibility

In order to establish the degree of reproducibility of the 425°F oxidation-corrosion test, five laboratories, including SwRI, have participated in a cooperative test program on three selected lubricants: O-60-13, O-60-23, and O-60-27. O-60-13 is an oil that shows sensitivity to air flow rate, whereas O-60-23 is extremely temperature sensitive.

The results obtained to date from the cooperative test program are given in Table 6. These data represent averages of two determinations in each case for Laboratories A, B, C, and D, while the SwRI values represent averages of three or more determinations. It should be remarked that all laboratories reported very good repeatability between individual determinations; however, as shown in Table 6, considerable variance between laboratories was obtained for one oil. Laboratories C and D were generally less severe in the values reported, particularly on O-60-13 which showed rather extensive oxidation in tests performed by the other three laboratories. Laboratory A reported a final viscosity on O-60-13 somewhat lower than B and SwRI; however, the value indicates that the same general level of deterioration was attained. Test reproducibility for oils O-60-23 and O-60-27 was satisfactory, although Laboratories C and D again obtained the lowest levels of oxidation.

Details concerning the conduct of the test have been solicited from all participating laboratories and although several minor deviations in procedure have been noted, no explanation is apparent for the mildness of results reported by Laboratories C and D. The most probable cause of differences between laboratories is slight variations between sample operating temperatures; however, in this work,the lowest sample temperature reported was for Laboratory B and the highest was for C. The range of sample temperatures reported at the specified air flow of 197 liters/hr is given by the following tabulation.

Laboratory	Heat Medium	Sample Temperature, °F
SwRI	Oil bath	422-423
A	Oil bath	421-422
B	Aluminum block	415-416
C	Aluminum block	425-426
D	Oil bath	422-423

These values were obtained with the heat medium at 425°F except in the case of Laboratory C which operated the aluminum block at 428°F. Several other minor test deviations were used by this organization: the test tube was 14 in. in length from bottom to joint instead of the specified 12 in., a Type 316 stainless steel metal coupon was used rather than Type 301, and the wire used in tying the metal specimens was Type 430 stainless steel rather than Type 304.

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TABLE 6. REPRODUCIBILITY OF 425°F OXIDATION-CORROSION TEST

	Sample Viscosity, cs/100°F		Sample NN, mg KOH/g		Overhead NN, mg KOH/g	Oil Loss, g
Laboratory	Initial	Final	Initial	Final		
		O-60-13				
SwRI	25.7	94.8	0.02	10.7	80.3	71
A	25.5	72.4	0.02	10.5	101.1	59
B	25.6	97.1	0.01	13.8	99.5	73
C	25.0	29.2	0.12(1)	0.9	6.7	36
D	25.5	30.0	0.02	0.6	10.6	28
		O-60-23				
SwRI	16.0	23.8	0.05	4.7	20.9	86
A	16.1	20.2	0.07	4.3	13.2	75
B	16.1	17.8	0.02	0.5	4.4	70
C	15.7	17.4	0.13(1)	0.4	3.7	51
D	16.0	17.4	0.05	0.3	5.7	60
		O-60-27				
SwRI	15.0	19.4	0.07	0.8	2.0	144
A	15.0	19.2	0.12	1.8	2.3	139
B	15.0	18.9	0.02	0.8	2.0	140
C	14.7	17.5	0.19(1)	0.7	2.0	117
D	15.0	17.9	0.10	0.6	2.8	119

Standard 18-hr test procedure (see appendix).

Values are averages of two or more determinations.

(1) ASTM D974 Colorimetric Method (all others by potentiometric method).

It is difficult to assess the effect of these minor test deviations but it is believed that the high sample temperature reported by Laboratory C should have caused correspondingly higher levels of oil deterioration than was reported. Laboratory C has subsequently requested additional oil samples and will rerun the tests in the very near future. Arrangements have also been made for Laboratory D to retest the three oils. An extensive investigation among all laboratories is not feasible due to the scarcity of oil on hand -- the supply of O-60-13 was completely exhausted in providing for additional tests by Laboratories C and D.

Since the entire cooperative test program was conducted over a period of about six months, one repeat test was recently conducted at SwRI to investigate the possibility of changes in oil characteristics during this time period. The data obtained were, however, very much in line with previous SwRI results.

Further analysis of the reproducibility of the 425°F test procedure will be withheld pending the outcome of the repeat tests by Laboratories C and D.

3. Investigation of Lubricants Using the Standard Test Procedure

At the request of ASD, 425°F oxidation-corrosion tests have been conducted on six oils under standard 18-hr test conditions. Results of these tests are given in Table 7. The three samples of O-61-19 were identified as Lot Nos. 231-G, 261-G, and 291-G. O-61-19 is of the same nominal formulation as O-60-27; however, it is apparent that some batch-to-batch variation existed as illustrated by the following summary of the individual tests on oils of this formulation:

	Viscosity Increase at 100°F, percent	Final NN, mg KOH/g
O-60-27	29, 30, 29	0.85, 0.90, 0.68
O-61-19-231	177, 216, 185	9.30, 9.33, 9.88
O-61-19-261	79	5.27
O-61-19-291	90	5.97

The results obtained on O-61-17, MLO-61-1012, and MLO-61-1013 indicate very good oxidation stability for these oils as evidenced by the viscosity increase and final neutralization number shown in Table 7.

4. Effect of Copper Specimen on 425°F Test Results

A modified 425°F oxidation-corrosion test was accomplished on six selected oils to determine the effect of copper on test results. This

TABLE 7. RESULTS OF 425°F OXIDATION-CORROSION TESTS

		O-61-19	O-61-19	O-61-19	O-61-17	MLO-61-1012	MLO-61-1013
Oil sample:							
Lot number:		231-G	261-G	291-G			
Viscosity at 100°F, cs:	Initial	15.74	15.70	15.62	15.92	15.00	15.30
	Final	44.81	28.04	29.71	17.76	15.61	15.96
	% Increase	184.7	78.6	90.2	11.6	4.1	4.3
Neut. no., mg KOH/g:	Initial	0.09	0.02	0.04	0.06	0.14	0.14
	Final	9.88	5.27	5.97	0.53	0.12	0.16
Overhead product neut. no., mg KOH/g		28.43	12.52	9.78	4.73	0.74	1.52
Overhead product collected, g		158.0	137.0	134.0	79.0	118.0	121.0
Oil loss, g		161.0	141.0	137.5	84.5	122.0	124.0
Metal weight change, mg/cm^2:	Al	-0.03	-0.05	-0.02	-0.01	-0.01	+0.02
	Ti	-0.03	-0.02	-0.01	0.0	0.0	+0.02
	Ag	-0.23	-0.09	-0.16	-0.04	-0.13	-0.05
	Steel	+0.05	+0.05	+0.01	+0.02	-0.02	-0.01
	SS	-0.03	+0.02	0.0	-0.02	-0.02	0.0

Standard 18-hr test procedure

was a standard 18-hour test except for the use of a copper metal specimen in place of the stainless steel specimen normally used. Table 8 compares the data obtained with that for the standard oxidation-corrosion test and the engine test. Results on oil deterioration with respect to final viscosity substantiate earlier work(5) on the development of the oxidation test. Questionable engine correlation exists for O-60-13 and O-59-26, since these oils showed much lower final viscosities in the oxidation-corrosion test with copper present. O-60-27 indicated a somewhat higher level of deterioration with respect to viscosity increase than the engine. More significant, however, is the fact that O-60-27 and O-61-19 (same nominal formulation) were not properly separated in performance by the test with copper, whereas engine data and standard oxidation test data indicate that O-61-19 deteriorated much more severely than O-60-27. It is further apparent that neither a reduction nor an increase in total test time would serve to remedy the discrepancies in viscosity correlation produced by the use of a copper specimen.

The effect of copper, as exhibited by the neutralization number data of Table 8, was significant only for O-60-23 and O-60-27. The use of copper gave a considerable decrease in neutralization number for O-60-23, but a large increase for O-60-27.

C. High-Temperature Oxidation-Corrosion Test

In accordance with the recommendations of the Bench Test Panel of the CRC Aviation Group on Gas Turbine Lubrication, a round aluminum heating block has been designed and constructed for investigating the oxidation-corrosion characteristics of high-temperature lubricants. The unit is intended to provide baseline performance data on oil deterioration properties under environmental conditions comparable to those encountered in supersonic transport aircraft.

1. Test Apparatus

Heating Block. The cylindrical heating block was constructed of forged 6061-S aluminum alloy. It was decided to forge the block rather than cast it, in order to ensure freedom from voids. Other workers in this field have reported a lack of uniform temperature distribution using a cast aluminum block, presumably due to the presence of voids within the metal.

The unit will accommodate eight sample tubes and was designed for a temperature capability of 800°F. Thermal insulation of the block is illustrated in Figure 24. Base insulation is provided by 4 inches of Johns-Manville Marinite 23A. The block rests directly on this material, which

TABLE 8. EFFECT OF COPPER ON 425°F OXIDATION-CORROSION TEST RESULTS

	Initial	Standard Test with Cu	Standard Test(1)	Engine Test(2)
	Viscosity, cs at 100°F			
O-58-24	34.65	130	184	220(20)
O-60-13	25.67	56.6	95	91(20)
O-60-23	16.02	17.8	23.8	19.7(100)
O-60-27	15.00	36.2	19.5	27.7(100)
O-61-19(3)	15.74	40.1	46.7	29(50)
O-59-26	18.67	27.4	41.5	37.8(40)
	Neut. No., mg KOH/g			
O-58-24	0.14	11.4	16.9	61(20)
O-60-13	0.02	8.7	10.7	12.9(20)
O-60-23	0.05	0.6	4.7	1.2(100)
O-60-27	0.07	8.1	0.8	3.1(100)
O-61-19(3)	0.09	9.4	9.3	5.0(50)
O-59-26	0.09	5.2	6.8	6.3(40)

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(1) Average value of two or more determinations.

(2) Numbers in parenthesis indicate hours of engine test duration.

(3) Same nominal formulation as O-60-27.

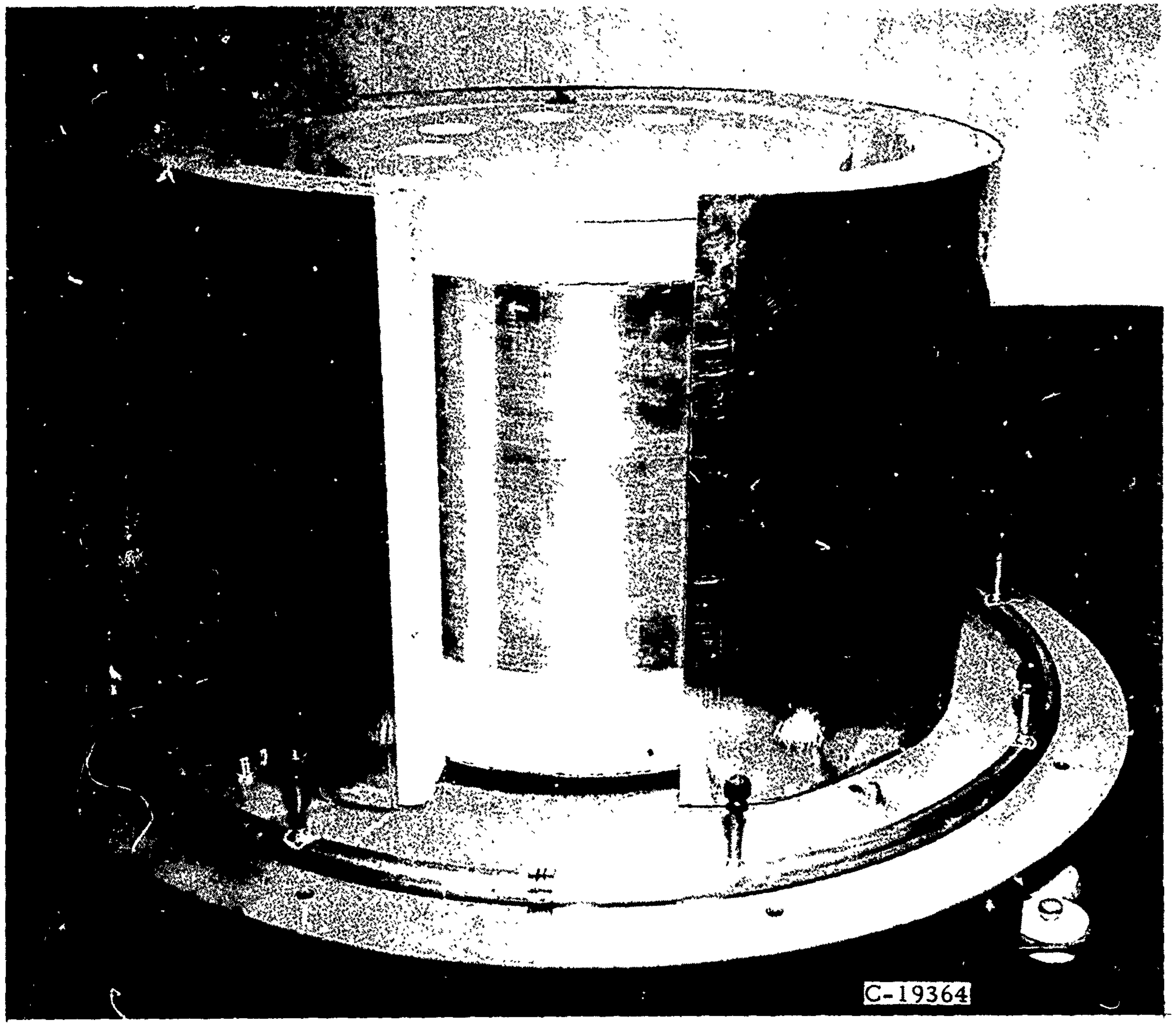

FIGURE 24. INSULATION FOR HIGH-TEMPERATURE OXIDATION-CORROSION HEAT BLOCK

possesses good strength characteristics. By this means, metal supports for the block were eliminated along with the accompanying high heat losses. The top insulation consists of 3 inches of Marinite 23A, and the side of the block is encased by a 3-inch thickness of Johns-Manville Thermobestos pipe insulation. Thermal conductivities for these materials at 500°F are 0.61 and 0.50 BTU/hour/ft^2/in./°F, respectively.

The block is equipped with sixteen, 300-watt, 230-volt, cartridge heaters. These units are 1 in. in diameter and 12 in. in length with a stainless steel sheath material. Eight of the heaters are equally spaced in a ring just outside the circle of the sample tube wells. These elements are operated in a continuously-on circuit with control accomplished by a variable transformer. The remaining heaters are equally spaced in a ring just inside the circle of the tube wells. These units are operated by means of a variable transformer and an on-off controller as illustrated in Figure 25. An independent safety switch is provided to shut-off the heating circuits in the event of a temperature rise of more than 10 to 15°F above the preset control temperature.

As will be discussed in a later section, it was found necessary to employ a heat-transfer medium between the block wells and the glass sample tubes in order to obtain maximum heat input to the sample. For this purpose, a 60/40 tin/lead solder is used which permits operation at a minimum temperature of approximately 400°F.

Test Glassware. The glassware employed in the high-temperature oxidation-corrosion test is of the same general configuration as that used in the 425°F test except as noted and described in the following paragraphs. The oil sample tube is constructed of standard wall 51-mm Pyrex tubing with a round bottom. A standard taper 71/60 outer joint is provided at the top of the tube. Overall tube length is 450 ± 10 mm, and the tube immersion depth within the aluminum block is 250 ± 10 mm.

The configuration of the tube head is illustrated in Figure 26. The overhead side-arm is attached to a water-cooled Graham condenser with a 250-ml round-bottom two-neck flask used as a condensate receiver . Vapors from the receiver are exhausted through a ring manifold which is vented to the building exterior.

A modification of the test tube head, not shown in Figure 26, is the addition of a standard taper 12/30 ground-glass joint. The joint is positioned 90° from the side-arm and permits oil sampling and oil temperature measurements without disturbing the assembly

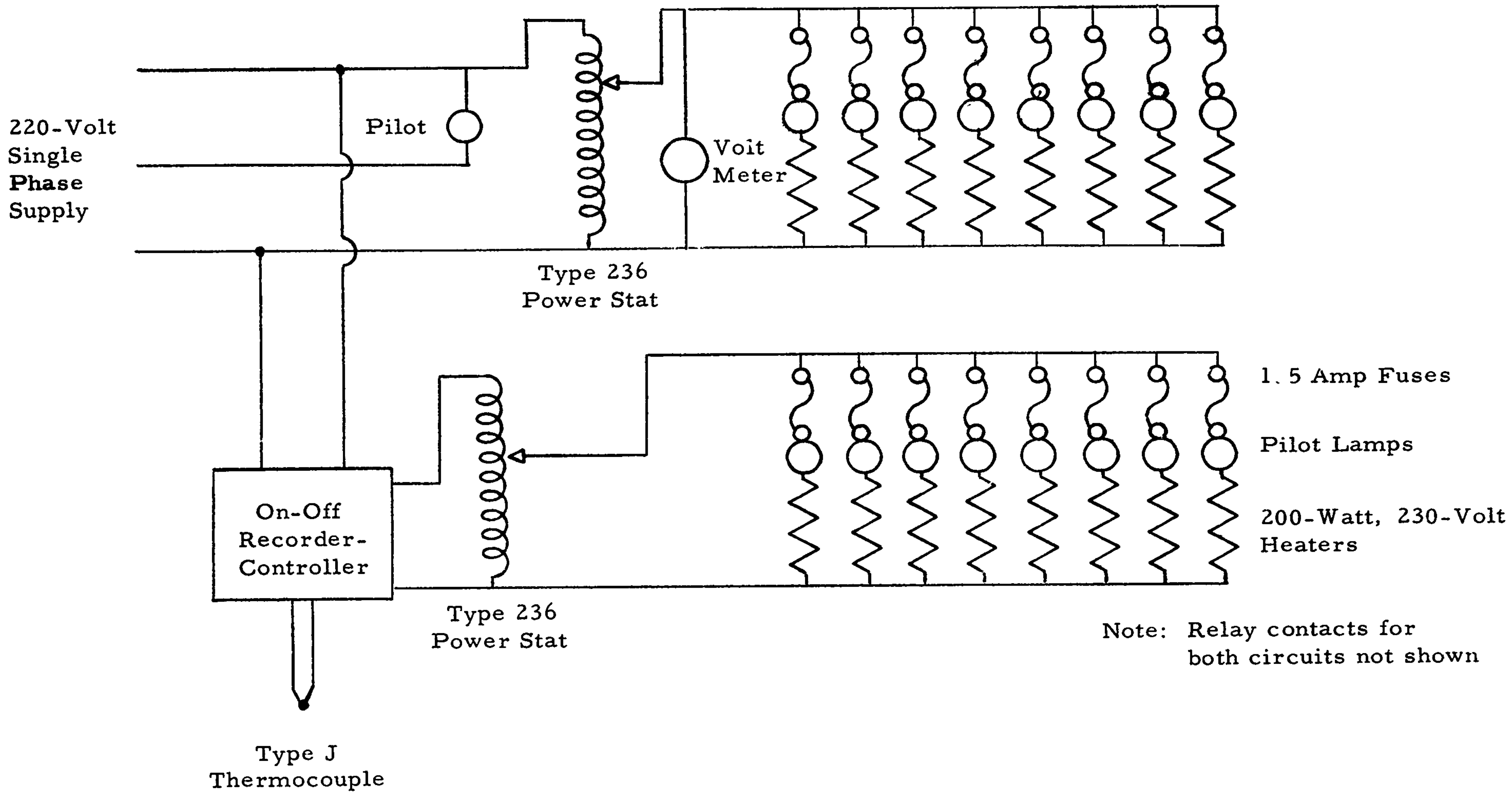
220-Volt Single Phase Supply
Pilot
Type 236 Power Stat
Volt Meter
On-Off Recorder-Controller
Type 236 Power Stat
Type J Thermocouple
1.5 Amp Fuses
Pilot Lamps
200-Watt, 230-Volt Heaters
Note: Relay contacts for both circuits not shown

FIGURE 25. SCHEMATIC WIRING DIAGRAM OF HIGH-TEMPERATURE BLOCK

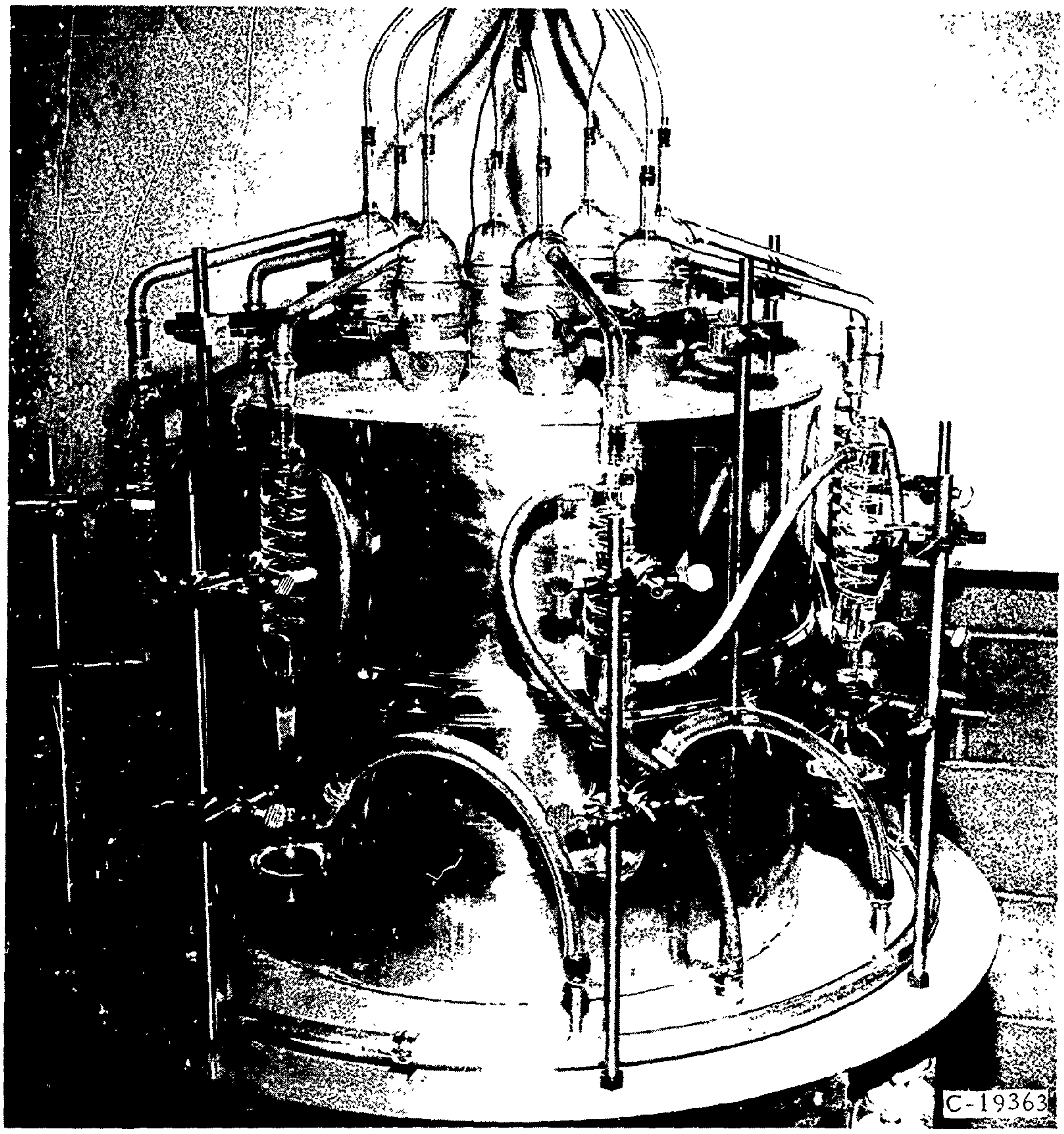

FIGURE 26. HIGH-TEMPERATURE OXIDATION-CORROSION TEST APPARATUS

An air delivery tube of standard 6-mm Pyrex tubing, approximately 600 mm in length, is fixed in the upper end of the head by means of a one-hole cork. The tip of the air tube is cut at a 45° angle and rests directly on the bottom of the sample tube. A small collar of sufficient size to hold the metal specimens is located 15 mm from the tip of the air tube. The bottom metal specimen rests directly on this collar and succeeding specimens are separated by a 1/4-in. glass spacer cut from standard 9-mm Pyrex tubing.

Air Supply System. A precision air regulator provides a constant air pressure to individual fine-thread needle valves from the laboratory air line. The air passes through a 4-in. glass pipe drying column, containing a calcium sulfate drier, and a manifold before reaching the individual test cell control valves and flowmeters. Each of the eight air flowmeters was calibrated by means of a wet test meter in order to provide accurate measurement of the air flow rate.

Metal Test Specimens. The metal specimens are of the round washer type with dimensions 3/4-in. O. D. by 1/4-in. I. D. by 0 032-in. thickness. Although the choice of a specific metal specimen group will be a matter of test investigation, the following material designations apply to the metals which will be used for the present:

Stainless steel	MIL-S-5059, Grade 301 Half Hard
Mild steel	QQ-S-636
Aluminum alloy	QQ-A-355
Titanium alloy	MIL-T-009046B (ASG), Class 1 (8% Mn)
Silver	Electrolytic grade
Copper	QQ-C-576
Magnesium	QQ-M-44a(1)

2. Test Procedure.

Since it is the objective of this program to explore the performance capabilities of high-temperature lubricant candidates over a wide range of test conditions, the use of a specific test procedure is not feasible at this time. Thus, a discussion will be given in this section of the anticipated limits of the test variables which will be investigated.

The break-temperature of the fluid will be determined to the nearest 25°F with 500°F being the minimum sample temperature employed. The maximum test duration will be 48 hours. Intermediate sampling is tentatively scheduled (dependent upon the extent of lubricant deterioration) for 16, 24, and 40 hours with an initial sample volume of 200 ml being used.

The break-temperature will be established using an air flow rate of 130 liters/hr and a metal specimen group containing the seven metals mentioned in the previous section. The effect of reduced air rates and/or the catalytic action of specific metals, particularly copper and magnesium, will then be investigated at the previously determined break-temperature.

Fluid inspection will consist of an evaluation of neutralization number, kinematic viscosity at 100°F, and existing sludge. Metal corrosion will be determined by weight difference and a visual examination for pitting or etching.

3. Test Results

Initial operation and temperature check-out of the aluminum block indicated very satisfactory performance to temperatures as high as 700°F. The adequacy of the block insulation is exemplified by the fact that at 500°F only 500 watts, of the total 4800 watts available, are required for operation (one-half of this power being used for on-off control). Further, excellent temperature distribution throughout the block has been recorded by thermocouples placed at varying depths around the perimeter of one sample tube. Temperature measurements by means of four thermocouple holes, equally spaced in a semicircle around one tube well, have indicated absolutely uniform temperature from a 9-in. depth up to approximately one inch from the top surface of the block. In addition, no difference in temperature was recorded between the eight sample tube wells at 500°F. However, extreme temperature differences were encountered between the block and the oil samples using an air well, i.e., without a heat-transfer medium. With a block temperature of 510°F and 130 liters/hr air flow, the sample temperatures ranged from 492 to 503°F with the polyphenyl ether, LRO-11, as the sample. After some investigation, these extreme variances were attributed to differences in O. D. of the glass test tubes, which affects the clearance between tube and block.

In view of the requirement for very close sample temperature control in oxidation tests in general, the use of a 60/40 tin/lead solder mixture was decided upon in order to obtain maximum heat transfer to the sample tubes. With the solder mixture in the tube wells, sample temperatures were 500°F for all eight test tube positions using a block temperature of 502°F. In addition, the sample temperatures remained unchanged throughout the air flow range of 25 to 130 liters/hr (measurements were made at 25, 50, 90, and 130 liters/hr). This would indicate that the heat loss due to air flow represents a minor portion of the total loss contributed by other factors.

Since the high-temperature oxidation-corrosion apparatus has just recently been placed in operation, only preliminary test data are available at this time. The initial test at 500°F included two MIL-L-9236 type oils, O-60-12 and O-60-23. These fluids had shown good oxidation stability in earlier standard 425°F oxidation-corrosion tests. However, the test at 500°F was obviously far above the oils' useful temperature. Tabulated results for duplicate samples are given in Table 9. Extreme and rapid oxidation was obtained on both lubricants, and the test was terminated after six hours. It is apparent that the repeatability between duplicate samples was very poor; however, it is felt that this was a direct result of the rapid oxidation rates involved. Minor differences in the conduct of the test were probably magnified considerably at these severe deterioration levels. No evidence of significant metal attack was obtained on either of these oils for the specimen group used.

The bulk of experimentation at 500°F has concentrated on two polyphenyl ether lubricants -- a four-ring material, LRO-11, and a five-ring material, LRO-13.

The results obtained to date on these oils are presented in Table 10. A brief study was made of the effect of air flow rate for LRO-11. This material showed relatively high oil losses at 500°F due to volatilization and/or oil mist entrainment. Using an air flow of 130 liter/hr, the entire sample was removed from the test tube within 48 hours. Succeeding tests at lower air rates served to reduce oil loss, generally in proportion to the air flow used. An illustration of recovered oil weights as a function of time and air flow is given in Figure 27. As indicated by the figure, the oil weights vary linearly with respect to time at any given air flow rate.

In all cases,oil deterioration, as indicated by viscosity increase and neutralization number, was very mild for LRO-11. One sample (at the lowest air rate used) was run to a total of 72 hours with a resultant viscosity increase of less than 5 percent. In addition, the extent of oil oxidation was generally unaffected by air flow rate within the range investigated. Similarly no change was noted in oil performance for the LRO-11 samples containing a magnesium or a copper test specimen.

No evidence of significant metal attack has been noted to date for LRO-11 or LRO-13 using the metal specimens listed in Table 10.

Results on LRO-13 have also shown a very mild degree of oil deterioration at 500°F with 130 liters/hr air flow. The viscosity increase on tests which were run to 72 hours was less than 10 percent and the final

TABLE 9. SUMMARY OF HIGH-TEMPERATURE OXIDATION-CORROSION TEST RESULTS FOR TWO MIL-L-9236 TYPE LUBRICANTS

Oil Code	Tests	Test Time, hr 0	2	4	6	Overhead Acidity, mg KOH/g
O-60-12	Vis, cs at 100°F	16.16	24.52	44.99	121.8	95.2
	% Vis Increase	-	51.8	179	653	
	NN, mg KOH/g	0.05	3.09	5.30	11.69	
	Overhead Wt, g	-	25.6	54.0	83.1	
O-60-12	Vis, cs at 100°F	16.16	26.38	53.29	201.0	110.8
	% Vis Increase	-	63.3	230	1140	
	NN, mg KOH/g	0.05	5.14	9.93	12.79	
	Overhead Wt, g	-	28.0	49.6	75.3	
O-60-23	Vis, cs at 100°F	16.08	27.07	50.20	155.4	159.5
	% Vis Increase	-	68.0	211	862	
	NN, mg KOH/g	0.06	3.66	6.19	10.93	
	Overhead Wt, g	-	27.6	54.1	79.2	
O-60-23	Vis, cs at 100°F	16.08	28.60	60.50	267.4	94.7
	% Vis Increase	-	77.5	275	1554	
	NN, mg KOH/g	0.06	4.78	8.42	13.63	
	Overhead Wt, g	-	29.6	54.8	86.3	

Sample temperature 500°F, air rate 130 liters/hr, metal specimens Al, Ti, Ag, steel, Stainless Steel.

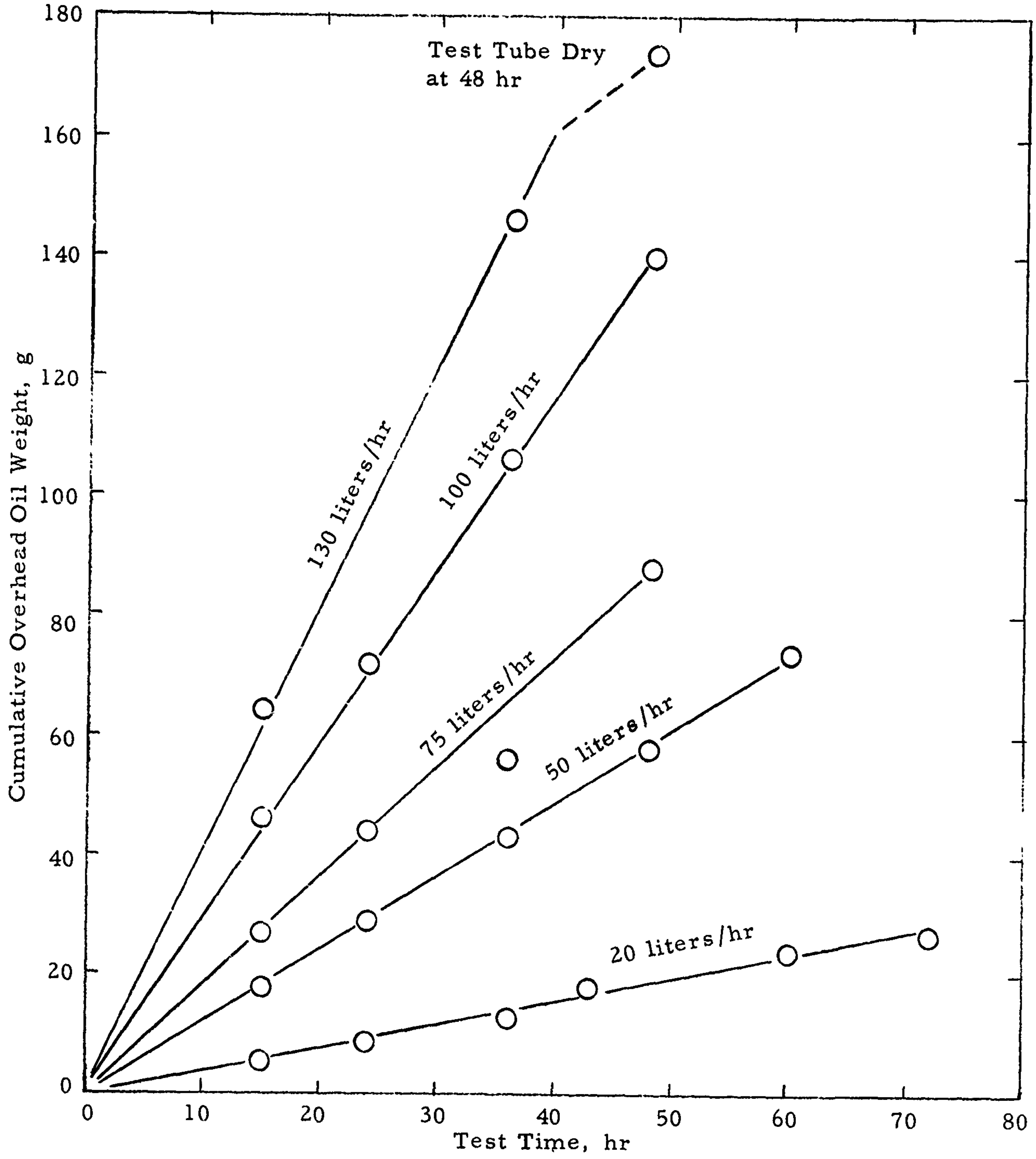

FIGURE 27. OVERHEAD LOSS FOR LRO-11 AT 500°F TEST TEMPERATURE

TABLE 10. SUMMARY OF HIGH-TEMPERATURE OXIDATION-CORROSION TEST RESULTS FOR TWO POLYPHENYL ETHER LUBRICANTS

Oil Code Air Rate	Tests	Test Time, hours							Overhead Acidity, mg KOH/g
		0	15	24	36	48	60	72	
LRO-11,	Vis, cs at 100°F	71.00	72.66	-	72.64	-(a)			0.0
130 liters/hr	% Vis Increase	-	2.3	-	2.3	-			
	NN, mg KOH/g	0.0	0.02	-	0.13	-			
	Overhead Wt, g	-	62.3	-	138.4	177.2			
LRO-11,	Vis, cs at 100°F	71.00	71.72	-	73.00	-(a)			0.0
130 liters/hr	% Vis Increase	-	1.0	-	2.8	-			
	NN, mg KOH/g	0.0	0.03	-	0.13	-			
	Overhead Wt, g	-	65.1	-	154.2	174.3			
LRO-11,	Vis, cs at 100°F	71.00	72.20	72.42	71.69	76.92			0.0
100 liters/hr	% Vis Increase	-	1.7	2.0	1.0	8.3			
	NN, mg KOH/g	0.0	0.0	0.0	0.0	0.0			
	Overhead Wt, g	-	45.8	72.5	106.2	140.5			
LRO-11,	Vis, cs at 100°F	71.00	72.47	72.05	72.63	73.62			0.0
75 liters/hr	% Vis Increase	-	2.1	1.5	2.3	3.7			
	NN, mg KOH/g	0.0	0.0	0.0	0.0	0.0			
	Overhead Wt, g	-	27.2	44.2	55.5	88.3			
LRO-11,	Vis, cs at 100°F	71.00	70.32	72.45	73.22	73.54	74.69		0.07
50 liters/hr	% Vis Increase	-	-1.0	2.0	3.1	3.6	5.2		
	NN, mg KOH/g	0.0	0.0	0.0	0.0	0.0	0.04		
	Overhead Wt, g	-	18.0	29.2	43.3	58.1	73.9		
LRO-11,	Vis, cs at 100°F	71.00	72.01	72.68	73.81	72.59	74.48	74.18	0.22
20 liters/hr	% Vis Increase	-	1.4	2.4	4.0	2.2	4.9	4.5	
	NN, mg KOH/g	0.0	0.0	0.0	0.0	0.0	0.0	0.03	
	Overhead Wt, g	-	5.7	9.0	13.0	18.0	24.2	27.2	
LRO-11,	Vis, cs at 100°F	71.00	72.00	71.64	73.14				0.0
130 liters/hr	% Vis Increase	-	1.4	0.9	3.0				
Copper added	NN, mg KOH/g	0.0	0.0	0.0	0.0				
	Overhead Wt, g	-	56.7	90.3	131.3				
LRO-11,	Vis, cs at 100°F	71.00	71.64	72.10	75.34				0.0
130 liters/hr	% Vis Increase	-	0.9	1.6	6.1				
Mg added	NN, mg KOH/g	0.0	0.0	0.0	0.0				
	Overhead Wt, g	-	64.0	101.5	147.5				
LRO-13,	Vis, cs at 100°F	362.4	378.6	-	379.7	389.6	393.8	395.4	0.04
130 liters/hr	% Vis Increase	-	4.5	-	4.7	7.5	8.7	9.1	
	NN, mg KOH/g	0.0	0.0	-	0.0	0.0	0.0	0.0	
	Overhead Wt, g	-	8.8	-	24.7	32.7	39.6	47.0	
LRO-13,	Vis, cs at 100°F	362.4	378.4	-	385.6	389.0	388.1	397.1	0.03
130 liters/hr	% Vis Increase	-	4.4	-	6.4	7.3	7.1	9.6	
	NN, mg KOH/g	0.0	0.02	-	0.0	0.0	0.0	0.0	
	Overhead Wt, g	-	18.9	-	22.3	29.5	34.8	41.7	
LRO-13,	Vis, cs at 100°F	362.4	381.1	-	384.4	-	382.8	397.2	0.02
130 liters/hr	% Vis Increase	-	5.2	-	6.1	-	5.7	9.6	
Copper added	NN, mg KOH/g	0.0	0.0	-	0.0	-	0.04	0.0	
	Overhead Wt, g	-	9.2	-	23.8	-	41.4	47.5	
LRO-13,	Vis, cs at 100°F	362.4	378.5	-	387.7	-	392.8	394.0	0.02
130 liters/hr	% Vis Increase	-	4.4	-	7.1	-	8.3	8.7	
Mg added	NN, mg KOH/g	0.0	0.0	-	0.0	-	0.0	0.0	
	Overhead Wt, g	-	8.4	-	20.5	-	34.7	39.8	

Sample temperature 500°F, metal specimens Al, Ti, Ag, steel, Stainless Steel, with Cu or Mg in place of Stainless Steel as indicated.

(a) Test tube dry at 48 hours

neutralization number was nil As with LRO-11, no effect on oil properties was apparent in tests with LRO-13 in which copper or magnesium specimens were used

D. Conclusions

A reproducibility program between five laboratories on the 425°F oxidation-corrosion test has yielded close agreement for three participants, with the two remaining laboratories reporting lower values for oil deterioration. Several minor deviations in test procedure were noted for one of the latter laboratories; however, no explanation is apparent at this time for the discrepancies of test results.

A modified 425°F test using copper has confirmed earlier observations on the deleterious effect of this metal on attempts to establish correlation with engine test performance data.

Operation and performance of the apparatus for high-temperature oxidation-corrosion studies have been very satisfactory. It is expected that the temperature capability of the unit will be much higher than the target temperature of 800°F.

Although only preliminary data are available at this time, two polyphenyl ether lubricants, LRO-11 and LRO-13, have indicated excellent oxidation stability at 500°F test temperature and at air flows up to 130 liters/hr. Oil loss for LRO-11, however, was excessive at air flows above 50 liters/hr. No effect on performance was evident for either fluid when copper or magnesium specimens were present

E. Future Program

Further analysis of the 425°F oxidation-corrosion test reproducibility will be made upon completion of repeat tests by two cooperating laboratories in the current program.

Future work in the area of high-temperature oxidation will concentrate on oil LRO-13 at temperatures above 500°F. The performance of the oil will be investigated at various temperatures and air flows in conjunction with selected metal specimen groups.

Additional high-temperature lubricant candidates will be included in this program as they become available.

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APPENDIX

OXIDATION-CORROSION STABILITY AT 425°F

(SECOND DRAFT)*

1. SCOPE

1.1 This method describes a test procedure for determining the susceptibility to oxidation and the metal-corroding tendency of aircraft turbine lubricants and similar high-temperature lubricants.

2. OUTLINE OF METHOD

2.1 This test consists of exposing a lubricant sample to the combined action of high temperature, a high rate of aeration, and the presence of metal specimens. After a controlled exposure period, the extent of lubricant deterioration and loss is measured, and the metal specimens are evaluated for overall or local attack.

3. APPARATUS AND MATERIALS

3.1 Bath. - Any bath may be employed that has provisions for maintaining a uniform temperature of 425 ± 2°F. The depth of the heating fluid and the configuration of the sample tube supports must be such that the oil sample level (within the tubes) is 2" ± 1/2" below the heating fluid level. This measurement is to be made without aeration of the test oil, with both the test oil and the heating fluid at operating temperature.

NOTE

Oil conforming to Specification MIL-L-6082, Grade 1100, is suitable as a heating fluid, provided low-intensity heaters are used for the bath. It is desirable to add an anti-oxidant (e.g., 1 percent phenyl α-naphthylamine) to this oil to extend its service life. For adequate temperature control, it is necessary that the bath be well insulated, well stirred, and controlled by a sensitive thermoregulator. The bath is equipped with a cover to accommodate the sample tubes, stirrer, and other necessary hardware, including a rack to support the bottoms of the sample tubes. The bath temperature may be read by any laboratory thermometer of the required range and accuracy; it is recommended that the accuracy of thermometer be checked periodically. It is further recommended that an auxiliary temperature record be provided by means of a recording instrument, and that an independent safety switch be provided to shut off the heating circuits in the event of a temperature rise of more than 10-15°F above the normal control point. It is also recommended that the bath should be located in a vented hood or provided with its own ventilating system.

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*September 22, 1961.

3.2 Oil sample tube and auxiliary glassware. - A sample tube and head in accordance with Figure 28 shall be used. An air delivery tube of standard 5-mm Pyrex tubing, approximately 610 mm in length, is fixed in the upper end of the head by means of a suitable one-hole cork. The remainder of the assembly includes a water-cooled Graham-type glass condenser and a 250-ml round-bottom two-neck flask used as a condensate receiver; the condenser is attached to the 19/38 joint on the head, and the flask is attached to the bottom of the condenser.

NOTE

Although the details of the condenser and condensate flask are optional, it is suggested that the condenser be approximately 200 mm in length with 19/38 joints on both ends, and that the flask be a standard 250-ml two-neck distilling flask with two 19/38 joints. The sample tube and head are available from Scientific Glass Apparatus Co.; the condenser and condensate flask are standard shelf items.

3.3 Air supply system. - The air supply system must be capable of metering 236 g/hr of clean dry air to each sample tube, maintaining this rate within ± 3 percent throughout the test period. This air flow rate is equivalent to 197 liters/hr measured at 70°F and 760 mm. The air shall be dried by passing through a column of Drierite or equivalent desiccant.

NOTE

The Drierite column should be made of glass, and the desiccant should include some indicating Drierite to

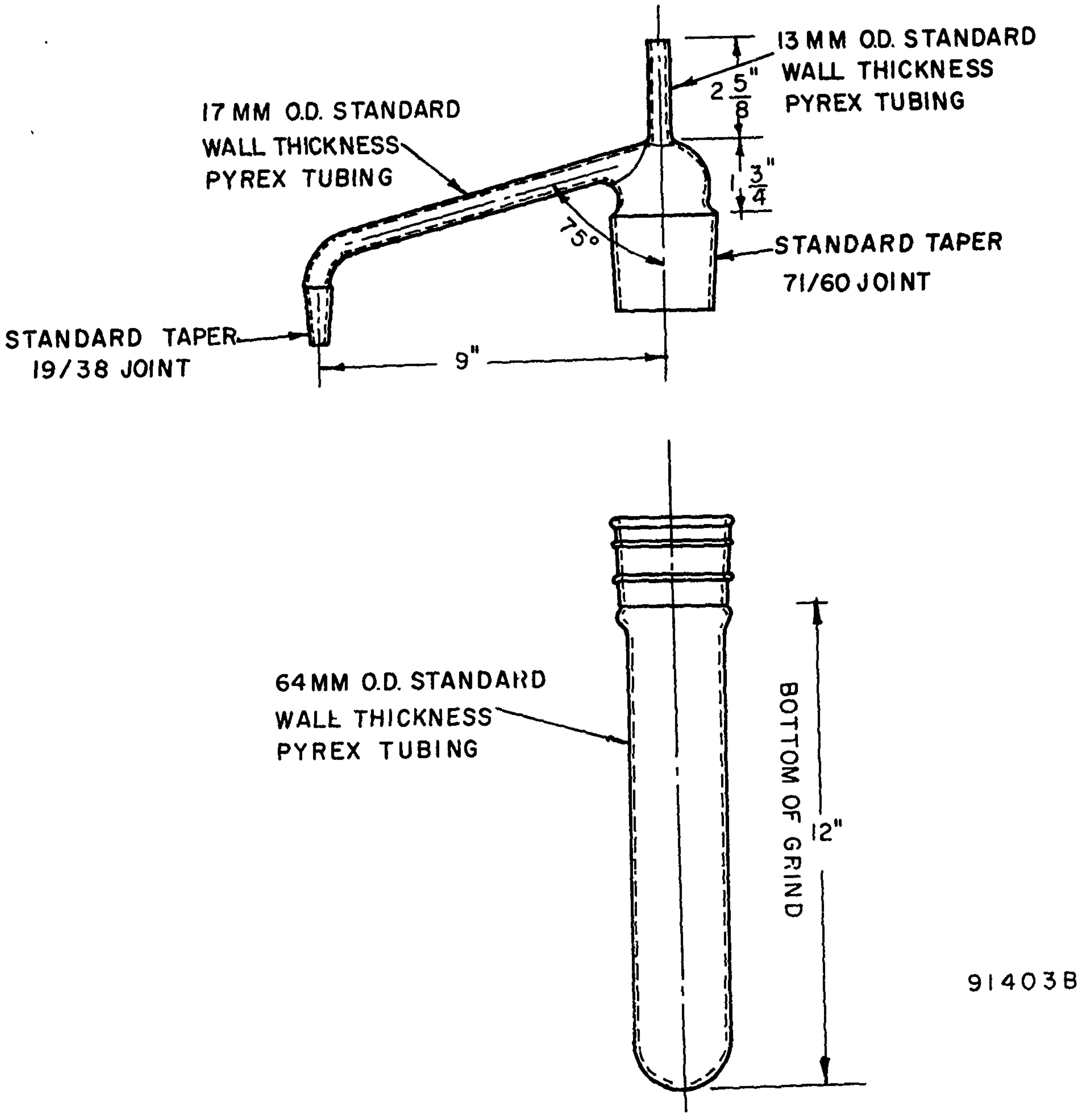

13 MM O.D. STANDARD WALL THICKNESS PYREX TUBING
$2\frac{5}{8}$"
17 MM O.D. STANDARD WALL THICKNESS PYREX TUBING
$1\frac{3}{4}$"
75°
STANDARD TAPER 71/60 JOINT
STANDARD TAPER 19/38 JOINT
9"
64 MM O.D. STANDARD WALL THICKNESS PYREX TUBING
BOTTOM OF GRIND
12"
91403B

FIGURE 28. TEST CELL AND HEAD FOR OXIDATION TEST APPARATUS

show when the desiccant needs changing. For a six-place test unit, a 4-inch diameter column of Drierite is necessary; the length of column required will depend on the moisture content of the entering air and the frequency of Drierite replacement that can be tolerated. The use of predried air (e.g., from a calcium chloride drying unit) is desirable in order to avoid too frequent changes of the Drierite.

3.4 Metal test specimens. - Specimens shall have dimensions as shown in Figure 29 and shall conform to the following metal specifications:

Stainless steel	MIL-S-5059, Grade 301 Half Hard
Mild steel	QQ-S-636
Aluminum alloy	QQ-A-355, T-3 or T-4
Titanium alloy	MIL-T-009046B (ASG), Class 1 (8% Mn)
Silver	Electrolytic grade (Handy and Harman 999 or equivalent)

3.5 Additional equipment.

Analytical balance, sensitive to 0.1 mg

Laboratory scale, sensitive to 1.0 g, capacity 5 kg minimum

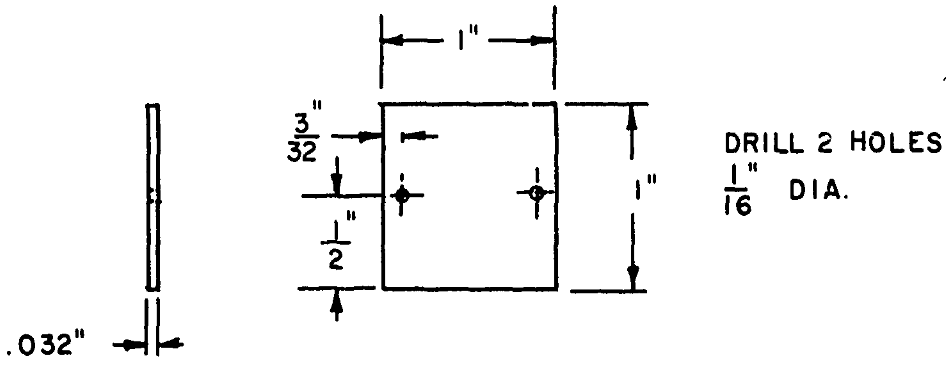
Microscope, 20X magnification

Sample tube racks, design optional (for handling and weighing)

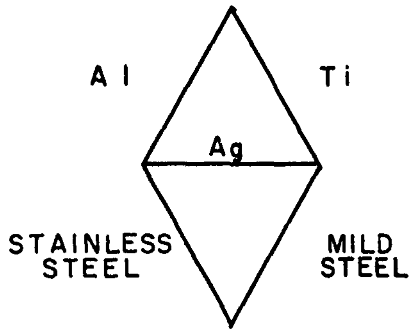
Wire screen strainers, 200 mesh - Fisher Scientific #13-583 or equivalent

Corks, for air delivery tubes, size No. 1 or No. 2, depending on size tolerance of top entry tube (on head)

Wire, 0.016 in., Type 304 stainless steel - Wilbur B. Driver Co., Nilstain Type 304 or equivalent


1"
3/32"
1/2"
1"
DRILL 2 HOLES
1/16" DIA.
.032"

TEST SPECIMEN


Al
Ti
Ag
STAINLESS STEEL
MILD STEEL

TEST SPECIMEN CONFIGURATION

91402 B

FIGURE 29. METAL SPECIMEN DIMENSIONS AND ASSEMBLY CONFIGURATION

Jigs for holding metal specimens for polishing and for assembly*

Long nose pliers

Stainless steel forceps

Graduated cylinders, 500-ml

3.6 Cleaning and polishing supplies.

Cotton gloves - H. Texture Glove Co., Plainfield, New Jersey, or equivalent

Cotton balls - Seamless Rubber Co., New Haven, Connecticut SR-9175 or equivalent

Cheesecloth, bleached, 28 X 32 count

Abrasive paper, 240 and 400 grit, 3M TRI-M-ITE Finishing Paper, Open Coat, Silicon Carbide

ASTM precipitation naphtha or ASTM iso-octane

Acetone, reagent grade, sulfur-free

Chloroform, reagent grade

Chromic acid cleaning solution

Concentrated sulfuric acid	1 liter
Saturated sodium dichromate solution	35 ml

4. PROCEDURE

4.1 Test Conditions. - The lubricant is exposed for 18 hours with a bath temperature of 425° F and an air flow rate of 236 g/hr. The lubricant sample volume is 350 ml, and one specimen of each of the five metals is present during the exposure period.

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*The polishing jig should be made of plastic, to avoid scratching the metal specimen surfaces; a suitable design is shown in Figure 30. The assembly jig may be made of metal, plastic, or a nonacidic hardwood such as maple, in any convenient design.

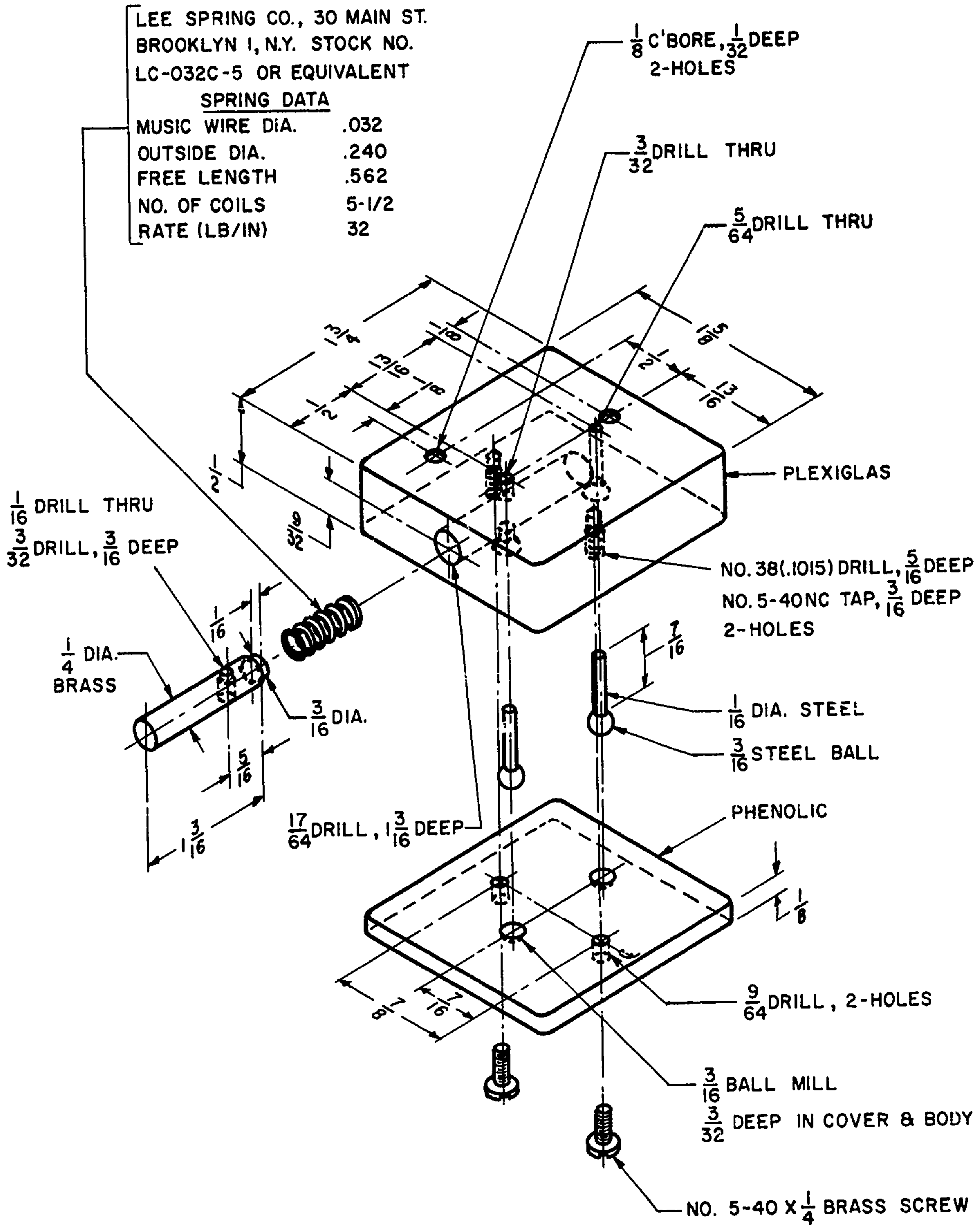
LEE SPRING CO., 30 MAIN ST.
BROOKLYN 1, N.Y. STOCK NO.
LC-032C-5 OR EQUIVALENT
SPRING DATA
MUSIC WIRE DIA. .032
OUTSIDE DIA. .240
FREE LENGTH .562
NO. OF COILS 5-1/2
RATE (LB/IN) 32
1/8 C'BORE, 1/32 DEEP
2-HOLES
3/32 DRILL THRU
5/64 DRILL THRU
1 3/4
1/8
13/16
1/8
1/2
1 5/8
1/2
1 3/16
1/2
9/32
PLEXIGLAS
1/16 DRILL THRU
3/32 DRILL, 3/16 DEEP
1/16
1/4 DIA.
BRASS
3/16 DIA.
5/16
1 3/16
17/64 DRILL, 1 3/16 DEEP
NO. 38(.1015) DRILL, 5/16 DEEP
NO. 5-40NC TAP, 3/16 DEEP
2-HOLES
7/16
1/16 DIA. STEEL
3/16 STEEL BALL
PHENOLIC
1/8
7/8
7/16
9/64 DRILL, 2-HOLES
3/16 BALL MILL
3/32 DEEP IN COVER & BODY
NO. 5-40 X 1/4 BRASS SCREW

FIGURE 30. SPECIMEN POLISHING JIG

4. 2 Preparation of metal specimens. - After preliminary degreasing and removal of any major pits or scratches by grinding, all surfaces of the specimen are polished with 240-grit silicon carbide paper to remove all previous marks, using fresh paper for each different metal. The specimens should not be touched with the hands, and should be handled only with clean cotton gloves or with forceps. A suitable jig should be used for holding the specimen during polishing. After the 240-grit polishing, the specimens may be stored in a desiccator over Drierite or calcium chloride. The final polishing with 400-grit silicon carbide paper should be performed immediately before the test is to be started, using fresh paper for each different metal. Only longitudinal strokes are used, and the polishing is continued until a clean blemish-free metal surface is obtained. During the final polishing and in subsequent operations, the specimen is handled only with forceps. After polishing, the specimen is swabbed vigorously with clean naphtha (or iso-octane) and with acetone to remove all metal particles and abrasive dusts, weighed to the nearest 0. 1 mg, and stored in a desiccator until the entire set of specimens is ready for assembly. The specimens are assembled in the configuration shown in Figure 29 and wired together. The wire (stainless steel as specified in Paragraph 3. 5) is cleaned with acetone prior to use. All handling of specimens and wires during assembly is accomplished without hand contact. A metal or maple jig may be used to hold the specimens during assembly. The wire is looped through the holes, twisted loosely, and the excess is trimmed off. The assembled specimens are given a final rinse in naphtha or iso-octane, allowed to dry, and stored in a desiccator until ready for actual installation in the test cell.

4. 3 Test startup. - A 350-ml sample of the test oil is measured into a clean, dry test tube, avoiding wetting the ground glass joint. (Additional oil sample, 30 ml minimum, should be set aside for determination of initial oil properties). The metal specimen assembly is added to the sample tube, and the air delivery tube is inserted so that its lower end rests within one of the triangles formed by the specimens. The head is put in place, using a very small quantity of silicone grease, and the air delivery tube is positioned by means of a tightly fitting cork so that its lower end is 1/8 in. off the bottom of the sample tube. This assembly (sample, sample tube, head, air tube, cork, and specimen assembly) is weighed to the nearest gram. It is then placed in the heating bath at 425°F and allowed to warm up for 15 minutes. During this time, the "overhead" assembly is completed; this includes connecting up the head sidearm to a condenser and tared (± 1 g) condensate flask and starting water flow through the condensers. The air delivery tube is connected to the metered air line. without any air flowing. At the end of the warmup period, timing of the test period is started, and air is introduced at a rate of 236 g/hr

4.4 Test period. - The bath temperature is maintained at 425 ± 2°F and the air flow rate at 236 g/hr ± 3 percent for a period of 18 hours ± 5 minutes.

4.5 Test shutdown. - At the end of the test period, the air flow is stopped, the air tube is disconnected, the head sidearm is disconnected from the condenser, and the tube-head assembly is removed from the bath, wiped free of oil, and allowed to cool. This assembly is then weighed to the nearest gram to determine oil loss. The oil sample is filtered through a 200-mesh screen into a sample bottle and retained for determination of properties.

NOTE

> Since the neutralization number of some oxidized oils will change markedly on storage at room temperature, it is essential that the oxidized oil sample be tested on the same day as drawn, or that it be stored at 20°F or colder to prevent change.

The condensate flask is weighed to the nearest gram to determine the amount of overhead product collected, and this product is retained for the determination of neutralization number, observing the same precautions on sample storage as described above. Observations are recorded on the appearance of the glassware with respect to sludge, varnish, or other deposits on all parts of the assembly, and sludge trapped by the filter screens. The metal specimen assembly is rinsed with acetone or naphtha as required to remove the oil and carefully disassembled. The individual specimens are placed on a mat of clean cheesecloth and swabbed vigorously with warm acetone and chloroform, using a series of fresh cotton swabs until clean swabs are noted. The specimens are not touched with the bare hands during disassembly and cleaning. After a final rinse in warm acetone and flash drying, the specimens are cooled in a desiccator and then weighed to the nearest 0.1 mg. The specimens are examined under 20X magnification for evidence of pitting, etching, or other attack.

4.6 Glassware cleanup - The glassware is rinsed with suitable organic solvents to remove all oil. The sample tubes, heads, and air delivery tubes are washed with soap or detergent and water. The air delivery tubes may be discarded if they are not readily cleaned. All of this glassware, whether new or precleaned by the methods described, is then soaked in chromic acid solution until all deposits are removed, then rinsed thoroughly with tap water and then with distilled water, and oven dried. The clean glassware may be protected with aluminum foil until ready for use. The condensers and condensate flasks are rinsed with suitable solvents as required to remove all oil and any deposits that are present. The condensers may be left in place during this rinsing. The joints on the condensers and condensate flasks are capped with aluminum foil after cleaning.

4.7 Determination of oil properties. - The total acid number is determined on samples of the original oil, oxidized oil, and overhead product, using the electrometric titration method (Fed. Test Method Std. No. 791, Method No. 5106.4) but titrating to 11 pH. The viscosity at 100°F is determined on samples of the original oil and oxidized oil, using a kinematic viscosimeter (Fed. Test Method Std. No. 791, Method No. 305.3).

5. REPORT

The total acid number is reported in mg KOH per gram oil for the original oil, oxidized oil, and overhead product. The viscosity is reported in centistokes at 100°F for the original oil and oxidized oil. The weight loss of the oil sample during test and the weight of overhead product collected are reported in grams. Visual observations of sludge, lacquer, or other deposits are reported. The metal specimen weight changes are reported in milligrams per square centimeter of metal surface. The condition of the metal surfaces is reported in terms of visual observations of pitting, etching, or other evidences of corrosion.

6. PRECISION

The repeatability and reproducibility of test results have not yet been determined.